VOL. XXXVI. — No. 5. MAY 1959.

Monthly Bulletin of the International Railway Congress Association

(English Edition)

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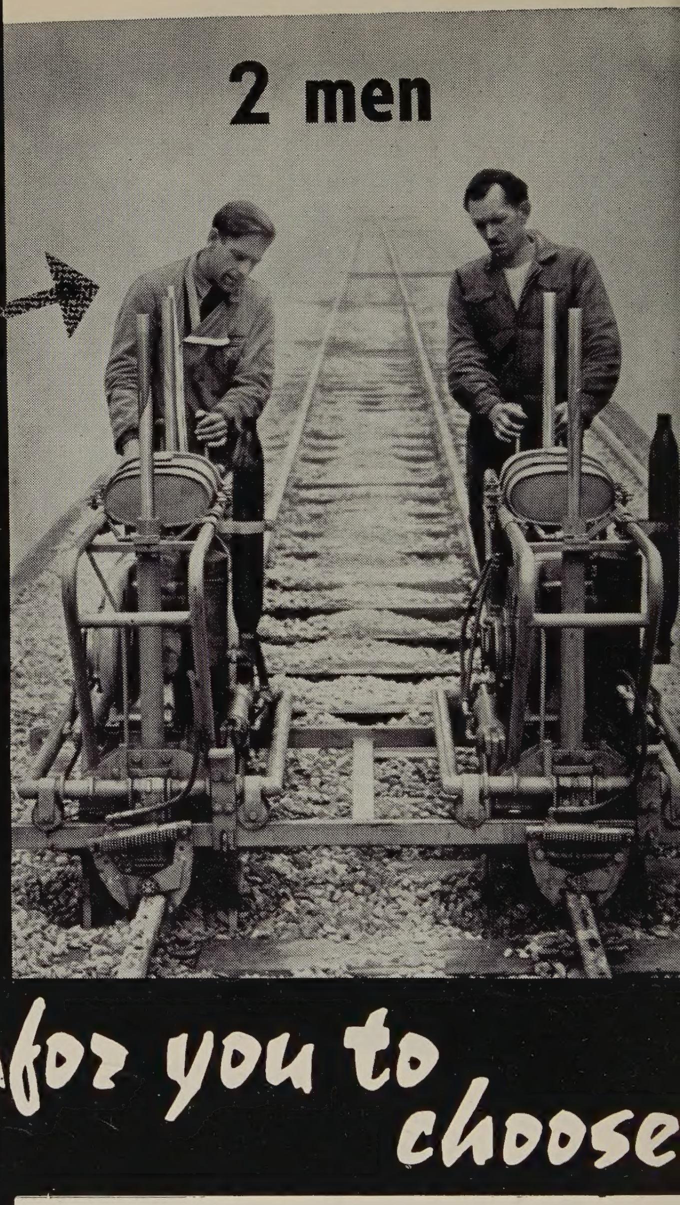

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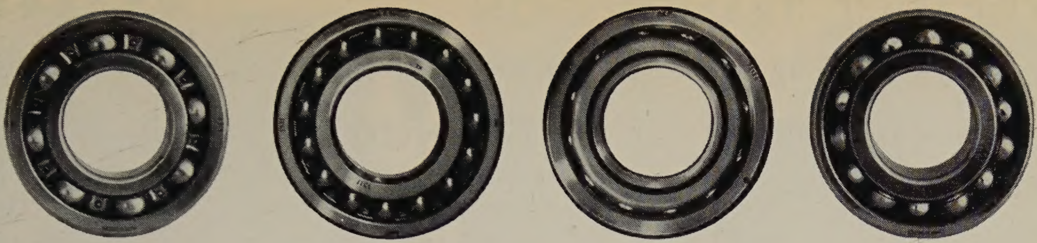

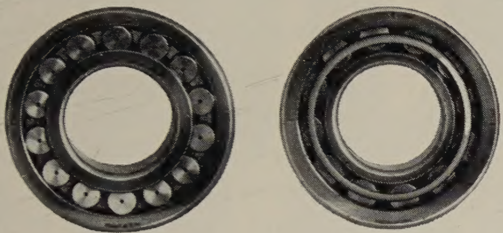

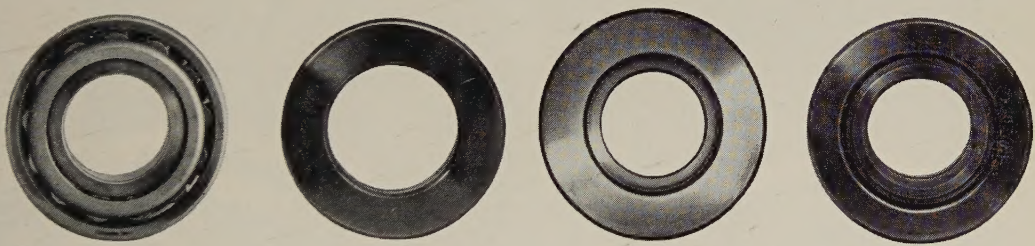

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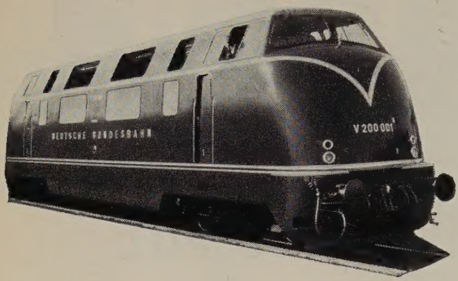

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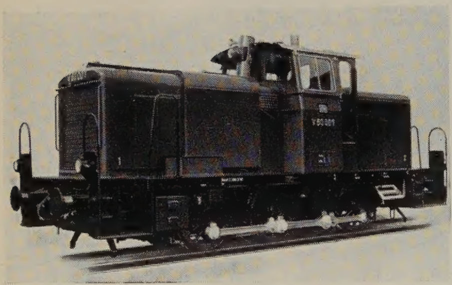

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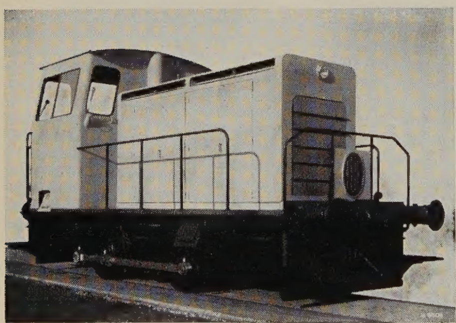

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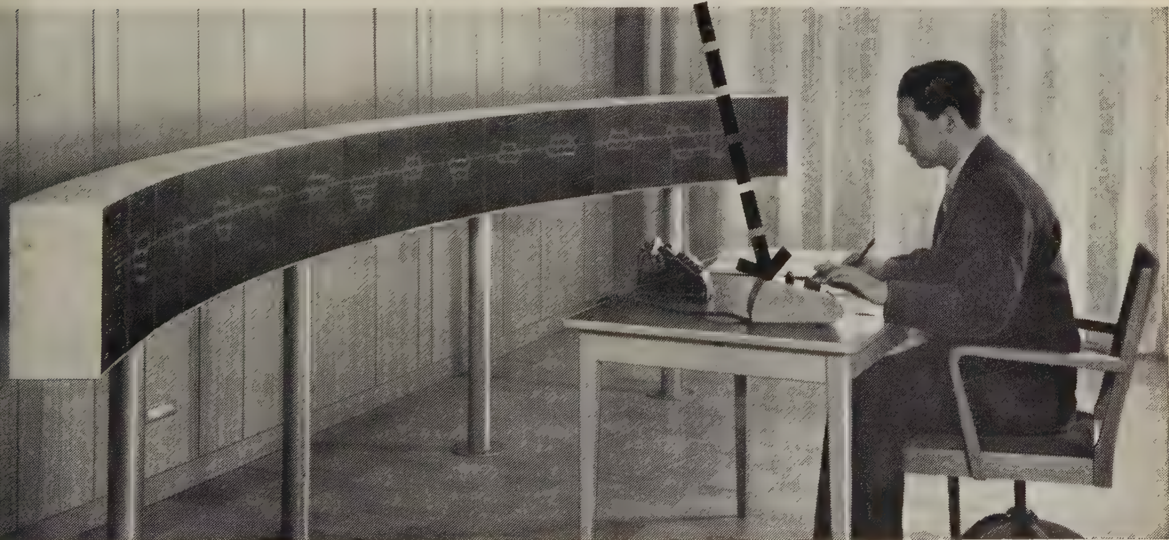

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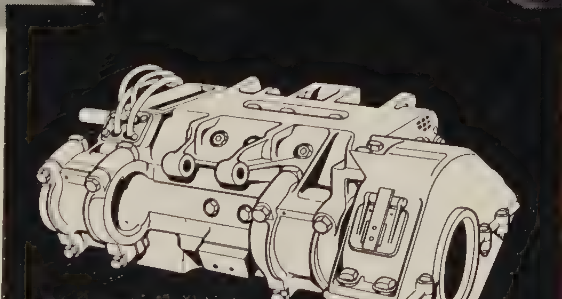

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BULLETIN
OF THE
INTERNATIONAL RAILWAY CONGRESS
ASSOCIATION
(ENGLISH EDITION)

[621 .436 & 621 .89]

Spectrographic analysis of lubricating oils for Diesel engines,

by J. RIGAUX, Ingénieur Civil U.I.Lv.
Ingénieur Principal Adjoint à la Société Nationale des Chemins de fer belges.

PRELIMINARY REMARKS.

The method of controlling Diesel engines by means of spectrographic analysis of the lubricating oils originated in the United States about ten years ago.

At present, this technique is used by some thirty American railroad companies.

About eighteen months ago, the Belgian National Railways decided to acquire the equipment necessary for carrying out the spectrographic analysis of lubricating oils. The equipment was taken into operation in June, 1958; it was manufactured by a Belgian company (M.B.L.E.) under Belgian licence (Macq).

In the present article, we shall examine successively :

— why the S.N.C.B. adopted the method of spectrographic analysis of oils;

— how the quantitative determination is carried out, and

— what results have been achieved so far by means of this technique.

The exposition will be divided into six chapters.

The first two chapters will deal with the principles which have guided the S.N.C.B. in applying the method of spectrographic analysis to lubricating oils.

The third and fourth chapters will be devoted to the description of the M.B.L.E. equipment and the analytical methods used.

The fifth chapter will deal with the first results obtained at the laboratory.

In the sixth chapter, we shall draw the conclusions.

Chapter I : Introduction.

Chapter II : Guiding principles for the control of Diesel engines by means of the spectrographic analysis of the lubricating oils.

Chapter III : Description of the M.B.L.E. equipment.

Chapter IV : Description of the method of analysis.

Chapter V : First results and information obtained by this control method.

Chapter VI : Conclusions.

1. Introduction.

The main objective of spectrographic analysis, as defined in the United States, is the detection of wear and of abnormal working conditions of Diesel engines by means of a quantitative analysis of the metal particles suspended in the lubricating oil. These particles emanate either from the Diesel engine itself or from the air which enters the engine through the air intakes.

The concentration of metal particles suspended in the oil is very low. The unit of measurement is the « part per million », or « p.p.m. », and corresponds to a weight concentration of 10^{-6}, i.e. 1 g of active matter per 1 000 kg of oil.

With each element, the content expressed in p.p.m. is variable but does not normally exceed 200 p.p.m. With certain elements, notably silver, the content is of the order of 1 p.p.m.

There is no conventional method of chemical analysis which would permit an accurate and rapid determination of such minute quantities. The only elegant solution of this problem of quantitative chemistry is provided by the method of spectrographic analysis.

The nine elements comprised in the analysis are these : silicon, iron, tin, silver, aluminium, lead, copper, boron, chromium.

The analysis programme is summarized in the following table :

Element	*Origin of the element*	*Purpose of analysis*
Silicon	Dust suspended in the air	To check the effectiveness of the air filters as well as the effectiveness of the air filter maintenance service
Chromium	1. Chromium-plated liners 2. Chromium-plated segments 3. Liners not chromium-plated, but cooling water of Diesel engine treated with chromates	1. } To ascertain liner wear 2. } To ascertain segment wear 3. To detect water leakages in the Diesel engine
Boron	Cooling water of Diesel engine treated with borates; liners chromium-plated	To detect water leakages in the Diesel engine
Iron	1. Dust produced by brake blocks 2. Liners, not chromium-plated 3. Segments, not chromium-plated 4. Crankshafts, pivots	Effectiveness of air and oil filters To ascertain the wear of these organs
Copper, Lead, Tin	Big-end bearings and crankshaft bearings	To ascertain the wear of the bearings
Aluminium	Pistons	To ascertain the wear of the piston grooves
Silver	Silver-plated pins	To ascertain the wear of the pins

As already mentioned, the elements suspended in the lubricating oil may emanate either from the engine itself or from the air entering the engine.

If we scrutinize the above table, we find that only aluminium and silver are characteristic for a specific organ.

It is therefore necessary to establish selection criteria which permit the determination of the origin of each element encountered in abnormal concentration.

These criteria are based :

1) on the chronological sequence of the appearance of the different metal particles in accordance with the logical progression of the wear or the origin of the anomaly;

2) on the absence or on the simultaneous presence of certain elements.

By way of example, and without claiming comprehensiveness, we shall examine some of these criteria.

Iron.

If the iron concentration increases regularly and progressively with the age of the oil filling, without any concomitant increase in the quantity of the other elements such as lead, copper and tin, the following conclusions can be drawn :

1) the presence of iron does not indicate any bearing trouble (absence of lead, copper and tin);

2) the iron can only emanate from the dust produced by the brake blocks which is sucked in with the engine air;

3) the oil filters are not effective as they would otherwise intercept the iron dust which has passed the air filters and the suction ducts.

Silicon.

If the silicon content increases with that of the iron, it can be concluded that the air filters do not work properly.

The presence of iron in the engine does not necessarily mean that the air filters are defective. They may be badly inserted and may absorb a quantity of brake dust which they are unable to retain.

Chromium.

If chromium is encountered simultaneously with iron in the case of engines equipped with chromium-plated liners, this will indicate abnormal wear of the liners. In particular, the concentration of these two elements will increase and will be comparatively high during the running-in period of a locomotive fitted with new liners.

Aluminium.

Aluminium is a sign of trouble at the segment grooves of aluminium pistons.

Lead, tin, copper.

Most frequently, these three elements appear in the following sequence : Pb, Sn, Cu. This sequence is in keeping with the progressive wear of the bearings. If the iron concentration increases abruptly, it can be concluded that a crankshaft or big-end bearing is worn. In the case of silver-plated pins, the silver content will rise to abnormal values.

Boron.

If there is a water leakage, the borate contained in the cooling water enters the Diesel engine. Normally, the boron content is insignificant. But it can rapidly assume important values even if the water leakage cannot be detected by conventional physical or chemical tests.

Frequently, the increase in the boron concentration is followed by an increase in the lead, tin and copper contents.

The water vapour combines with the combustion products, especially with the sulphur trioxide, forming acids which attack the white metal very quickly.

The crux of the problem of the spectrographic control of lubricating oils is the determination, for each element, of critical limits, taking into account:

1) the case history and age of the engine, and the age of the oil filling concerned;

2) the relations which may exist between several elements;

3) the specific characteristics of the engine and of its accessories;

4) the type of oil used.

In Chapter 2, it is proposed to outline the method used for determining these levels.

2. Guiding principles for the interpretation of the results of the spectrographic analysis.

2.1. *General.*

In the following exposition, we shall use the term « reconditioned engine » for a Diesel engine where the liners, segments, big-end bearings and crankshaft bearings have been systematically replaced, and the term « overhaul engine » for a Diesel engine where the systematic replacement has been confined to the segments whilst the bearings have only been replaced occasionally.

Let us consider a reconditioned engine. During the running-in period,

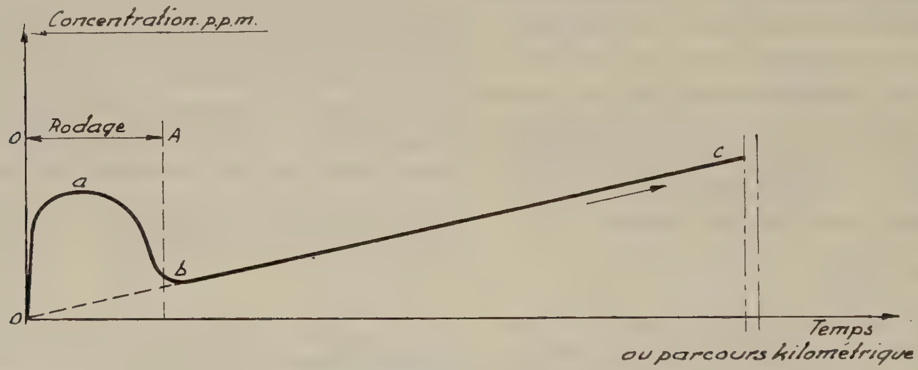

Fig. 1. — Typical concentration curve.

Explanations of the French terms :

Abscissa : time, or kilometrage. — Ordinate : concentration in parts per million.
Rodage = running-in period.

there will be a high concentration of certain elements while the different moving organs must adapt themselves to each other. In particular, the iron-chromium-tin-lead concentration may assume abnormal values. This phenomenon is similar to that encountered when a new engine is taken into operation.

period, and the zone *b c* the period of normal progressive wear.

In this diagram, we assume that the variation in the concentration as a function of normal wear is linear; experience will show whether or not the actual curve will conform to this assumption. At this stage of our exposition, inciden-

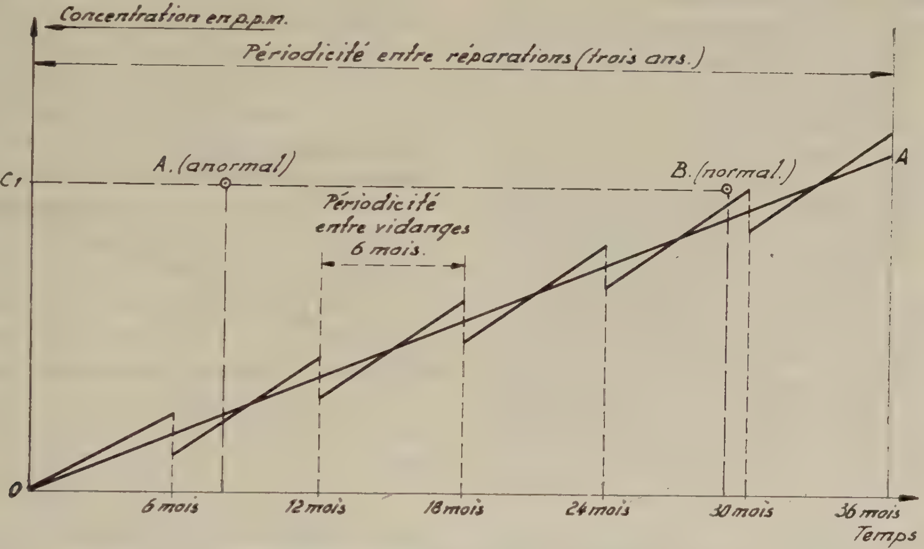

Fig. 2. — Typical concentration curve, taking oil changes into account.

Explanations of the French terms :

Abscissa : time in months. — Ordinate : concentration in parts per million.
Périodicité entre réparations (trois ans) = normal interval between repairs (three years). —
Périodicité entre vidanges (six mois) = normal interval between oil changes (six months).

As the running-in process continues, the concentration of these elements must decrease, up to the time when normal wear takes place and the concentration of the different elements increases progressively.

Figure 1 shows the variation in the concentration of an element as a function of the time in service or the kilometrage covered, assuming normal wear. The zone *o a b* represents the running-in

tally, it matters little whether or not the general shape of the graphs shown corresponds to real conditions, as the graphs are only meant to serve as examples so as to facilitate the description of the method.

If the engine has only been overhauled, the influence of the running-in period on the concentration of the elements will be negligible, and the curve *o a b* will be replaced by the section *o b*

which represents an extension of the straight line *b c*.

Figure 1 would show the increase in the concentration of metal particles in the oil which would take place if the oil bath would not be modified during the interval between two overhauls or reconditionings, a period which we assume to be three years.

During that period, the condition of the oil bath is affected by three factors : the changing, topping up of the oil, and the filter changes.

When the oil is changed, the bulk of the elements suspended in the oil is removed, and if the peptisation of a metal element by the detergent oil has been effective, the metallic deposits in the engine must be reduced. After the oil change, the first analyses will show an abrupt drop in the concentration. Topping up will only have a noticeable influence on the concentration if the quantity of oil added to the bath exceeds 10 % of the total bath.

Filter changes, if carried out correctly, should also reduce the concentration of impurities.

In figure 2, we have plotted the variation in the concentration in the intervals between oil changes which are assumed to take place every six months, so that the diagram has the corresponding saw-tooth shape. Line *O A* represents the mean concentration.

In order to simplify this diagram, the influence of the running-in period (zone *o a b* in fig. 1) has been neglected, on the assumption that the engine has only been overhauled.

Figure 3 shows graphically the influence of filter changes at shorter intervals, say one month. The influence of filter cleaning (once every ten days) can be neglected if a point is made of taking the samples on dates fixed in relation to the cleaning cycle.

A combination of diagrams 2 and 3 yields diagram 4.

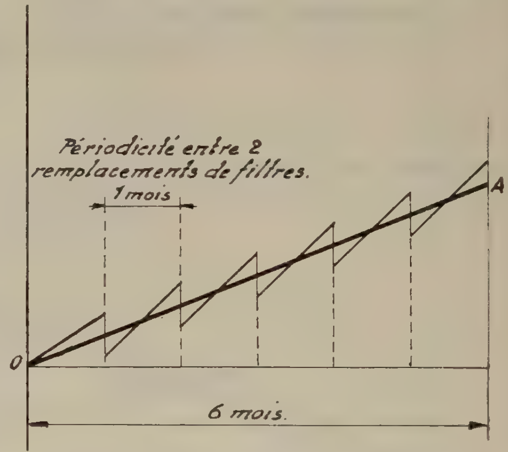

Fig. 3. — Influence of filter changes on the typical concentration curve.

Explanations of the French terms :

Mois = month(s). — Périodicité entre deux remplacements de filtres = interval between two filter changes.

It has already been mentioned in Chapter 1 of this exposition that it is the purpose of the spectrographic analysis to detect abnormal wear and the risk of damage by examining the concentrations of wear metals suspended in the oil.

To achieve this objective, it is above all, necessary to know, for each type of engine and with due regard to the engine characteristics, the variation in the concentration of these elements in the case of a « normal » engine life.

In other words, it is necessary to determine, for each element, the concentration curve as a function of time or of kilometrage covered.

A concentration will then be abnormal if it exceeds the value indicated by the normal curve, and normal if it runs close to the latter.

Also, because of the general alignment of the curve, a given concentration may be normal at the end of the maintenance interval yet abnormal, i.e. excessive, at the beginning of the interval.

We shall reserve the adjective « excessive » for a concentration which indicates incipient damage.

It is obvious that the chart points obtained will show a dispersion in relation to a theoretical line, for the following reasons :

1) the method of analysis consists of a series of elementary operations such as sample-taking and sample preparation, each subject to errors and inaccuracies;

2) for reasons which we do not know, or are beyond our control, the concentration of certain elements may increase abruptly. For example, in the case of a filter change, lack of proper care may entail an abrupt increase in the concentration of certain elements caused by the fact that impurities retained by the filter are suddenly released into the oil circuit;

3) two locomotives with the same engine outfit and maintained at the same depot do not show an identical progression of normal wear.

Finishing tolerances, heterogenities of the constituent materials (bronze, white metal), variations in the effectiveness of the filters are among the several factors which affect the working conditions and, thus, the progression of wear.

In spite of the inevitable scatter of the concentrations, it is possible to establish sufficiently precise criteria. This is because, for one thing, the straight lines appearing in diagrams 1, 2, 3, 4 can be replaced by zones in order to take the dispersion of the readings into account and secondly, the variation in the concentration of the elements concerned in case of abnormal or excessive wear is so rapid that the concentrations are several times greater than the normal concentrations, and the corresponding point in the chart is clearly outside the normal range.

For each type of locomotive where the engine is subjected to spectrographic control, it is necessary to determine the concentration curves because the concentration of the different elements is influenced by such factors as the nature and dimensions of the constituent organs, the volume of the oil bath, the quality of the filters, all of which may vary with the type of engine.

With a main line locomotive, the engine crankcase contains about 700 kg of oil. A copper content of 30 p.p.m. corresponds to 21 g of copper suspended in the oil.

With a shunting locomotive, where the crankcase contains 300 kg of oil only, a copper content of 30 p.p.m. corresponds to 9 g of copper only.

Yet, in the case of a small engine, the sum of the friction surfaces (bearings, pistons, journals, etc.) related to the volume of the oil bath is relatively greater than in the case of large engines.

It will therefore be possible to admit higher normal concentrations with a small engine than with a large engine.

It may be pointed out in passing that the spectrographic analysis does not measure the total quantity of the metallic elements contained in the crank case but merely the fine particles suspended in the oil.

If this control method is to yield a true picture of the engine life, the analyses must be carried out at fairly short intervals which, for main line locomotives, may mean three to four times a month. With shunting locomotives, a bi-monthly analysis appears to be sufficient.

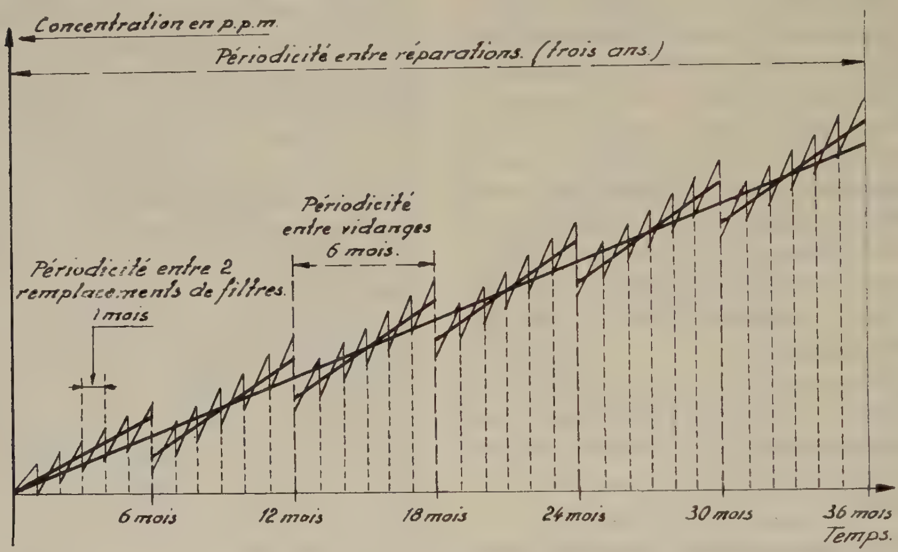

Fig. 4. — Typical concentration curve, taking into account oil changes as well as filter changes.

Explanations of the French terms :

Abscissa : time in months. — Ordinate : concentration in parts per million. Périodicité entre réparations = interval between repairs. — Périodicité entre deux remplacements de filtres = interval between filter changes. — Périodicité entre vidanges = interval between oil changes.

The relatively short interval is necessary because :

1) the rate of progress of a case of damage may be very rapid so that, with montly intervals for main line locomotives, there is a risk that most cases of damage remain undetected. A closer interval, on the other hand, would be too onerous. In fact, the choice of the interval represents a compromise which ensures the maximum effectiveness of the method at a reasonable cost;

2) in order to determine the alignment of the concentration curves of the kind shown in diagram 4 sufficiently rapidly, it is necessary to determine a

great number of points spaced at fairly close intervals.

If the results of the analysis of a sample, taken in accordance with the schedule indicated above, appear to be clearly abnormal, samples must be taken at closer intervals and analyses carried out, say, every other day in order to ascertain whether the results can be confirmed. After three or four readings, one will know whether the abnormal concentrations become excessive so that the engine must be taken out of service or whether the first abnormal result was merely fortuitous.

The calibration curves representing typical concentrations are determined empirically.

By repeating the readings with different engines of the same type at close intervals, and by comparing the results and readings of samples from engines in the depots and workshops, it is possible to determine these calibration curves for a normal engine, and to measure the influence of oil and filter changes on the changes in the concentration of metallic elements suspended in the oil.

The laboratory is installed in the central workshops charged with the overhaul and reconditioning of Diesel engines. The leader of the laboratory will thus easily be able to inspect the engines coming in for repairs and to verify the diagnosis based on the spectrographic analysis, thus making sure that the latter has not only an academic interest.

By comparing the readings of the analysis with the results of the examination of the engine on being dismantled, it will be possible to establish precise criteria which will permit the early detection of incipient damage.

It may be mentioned in passing that the laboratory also carries out such conventional physical and chemical analyses as viscosity tests, chromatographic tests, flash point tests, acidity tests, etc., which form part of the normal routine of all laboratories for the control of lubricating oils.

2.2. *Objectives of the spectrographic analysis.*

We shall conclude this chapter by outlining the objectives which we have set out to achieve by means of the spectrographic control of lubricating oils.

1) *Control of the quality of air and oil filters.*

Generally speaking, the filtration problem is poorly or imperfectly solved as far as Diesel locomotives are concerned. The part played by oil filters is often underrated.

In the absence of precise criteria which permit a proper selection of the filters and an assessment of their effectiveness, Diesel engine operators must often be content with a filter system which, if not totally inadequate, can only be regarded as mediocre.

In the chapter dealing with the results obtained from the spectrographic analysis, we shall have occasion to show the great influence of the quality of the filter on the concentration of the elements contained in the oil. By comparing the results obtained from the measurement of concentrations of the same

element on two identical locomotives fitted with two different filters it is possible to illustrate the respective quality of the filters.

2) *Control of the effectiveness of filter maintenance.*

If the filters are of proven quality, it is possible to detect any negligence on the part of the depots charged with the cleaning and replacement of the filter elements, by comparing the results of oil samples and watching the deviation of the actual concentration curves from the theoretical curves.

3) *Life of the oil bath.*

At present, the use of detergent oils is general practice for all Diesel engines. In the case of high-speed engines, detergent oils are recommended by nearly all engine manufacturers. In particular, these oils prevent the sticking of piston segments by keeping the combustion residue in suspension. On the other hand, the concentration of metallic elements peptised by the oil increases.

This phenomenon is further accentuated by increasing the intervals between oil changes. To our knowledge, however, none of the physico-chemical controls applied to oils take into account the concentration of the elements maintained in suspension. In our opinion, these elements act as abrasives and accelerate the wear of the engine, if they exceed a certain concentration.

We hope that, by means of the spectrographic analysis, we shall be able, not to prolong unduly the life of the oil bath, but to keep a check on it and reduce it if necessary. In our opinion, the abrasive wear caused by excessive intervals between oil changes is infinitely more expensive than the saving resulting from the extended life of the oil bath.

We shall have occasion, later on, to illustrate the importance of this question by examples from actual practice.

In the present exposition, we shall merely discuss the influence of the spectrographic analysis on the life of the oil bath. It goes without saying that the other control methods mentioned above fully retain their value and assist in the general control of the oil bath.

4) *Optimum engine output.*

By means of comparative tests, we hope to be able to show the influence of the regulation of the power of the Diesel engines on the rate at which engine wear progresses. This point must not be neglected if the present trend towards higher power/weight ratios is taken into account.

5) *Prevention of damage.*

We shall, later on, have occasion to show how it has been possible to detect bearing trouble, cylinder head fractures, leakages at the water-oil exchangers, by comparing the results of the analysis with the calibration curves by means of the method described above.

3. Description of the M.B.L.E. direct-reading spectrograph.

3.1. *General.*

The principles discussed at the outset of this exposition, which have guided

us in the application of the spectrographic analysis to Diesel engines, have compelled us to use a method of analysis with a high degree of « repeatability ».

In keeping with American definitions, we use the term « repeatability » to designate the aptitude of a given equipment to reproduce the same reading of the same sample in a given laboratory by the same operator.

The repeatability of the readings will depend on two factors :

1) the preparation of the sample which must ensure a good homogeneity of the oil analysed;

2) the whole of the apparatus, comprising the spectrographic equipment, as well as the method of analysis.

In the following chapter, we shall examine how the samples are taken and prepared to ensure a good repeatability of the readings.

We merely wish to draw the attention of the reader to the fact the equipment and method for the analysis have been chosen in such a way as to minimize those manipulations and operations which may entail reading errors and thus impair the repeatability of the method.

Up to about ten years ago, spectrographic recording was carried out exclusively by photographic means. All the various stages of work inherent in that method, such as calibrating the films, developing, fixing and washing of the sample films and measuring their density, represent so many steps adding to the risk of errors, and thus reduce the repeatability.

In order to avoid these contingencies as much as possible, the S.N.C.B. decided to acquire a direct-reading equipment.

As the elements which it was intended to measure were known and could be covered by an always identical programme, a direct-reading equipment was the obvious choice.

Due to the speed with which the analysis can be carried out the leader of the laboratory is now able to devote most of his time to the interpretation of the results and the control of the engines.

3.2. *Description of the M.B.L.E. spectrograph (Macq licence).*

3.2.1. *General principles of emission spectroscopy.*

When atoms or ions are raised to a high temperature, the electrons undergo electronic layer transitions by absorbing energy. When reverting to their initial trajectory, they emit monochromatic radiations of a wave length depending on the quantum of energy absorbed.

If a specific monochromatic radiation of the element concerned is selected and isolated, it is possible to quantify the element by measuring the intensity of that spectrum line.

With spectral analysis, the important thing is therefore to utilize such lines that their origin is not in doubt. Moreover, these lines must be relevant to the problem to be solved.

In our case, the concentrations to be measured are very low, and it was necessary to choose, for each element, an

« ultimate line ». As the term indicates, the ultimate lines are the last ones to disappear when the concentration of the elements approaches zero.

It should be mentioned, in passing, that the lines which we have chosen may be different from those used for the measurement of the same elements in the metallurgical industry, as the concentrations there encountered are much higher, and less intense lines must be used.

Moreover, the selection of the lines is also governed by the analysis programme. A spectrum line, however excellent, cannot be used if it interferes with another one too close to it which also corresponds to the programme but applies to a different element.

The nine lines measured by us range from 2 496 Å to 4 254 Å. Figure 5 shows the position of these lines in relation to the visible spectrum. The wave length is expressed in Angströms.

Below each spectrum line, we have marked the element measured by its chemical symbol. With the exception of the chromium line which is at the beginning of the visible spectrum, all the lines are in the ultraviolet zone.

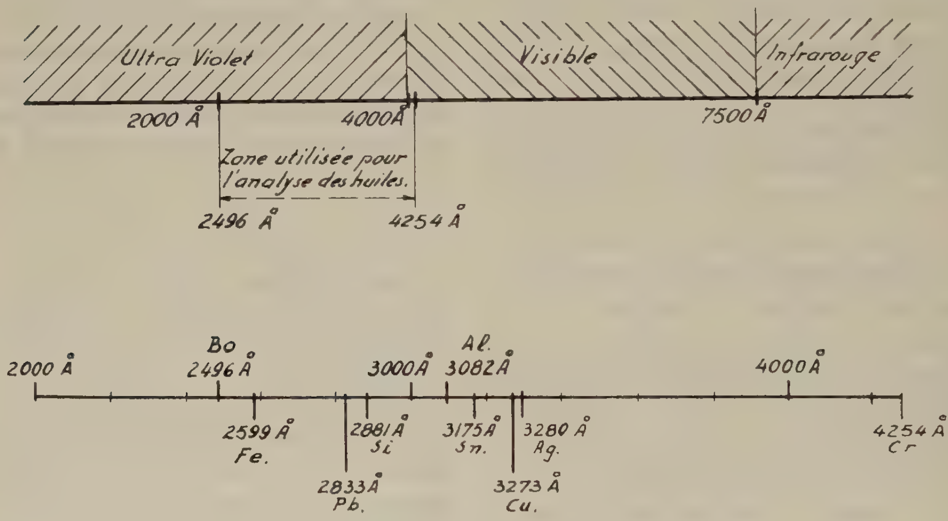

Fig. 5. — Spectrum lines used for the spectral analysis.

Explanations of the French terms :

Infrarouge = infra-red. — Zone utilisée pour l'analyse des huiles = zone used for the analysis of oils.

The equipment needed for the spectrographic analysis must conform to a threefold programme :

1) create the excitation of the atoms of the elements to be measured, by raising their temperature;

2) decompose the radiations produced by this excitation into monochromatic radiations;

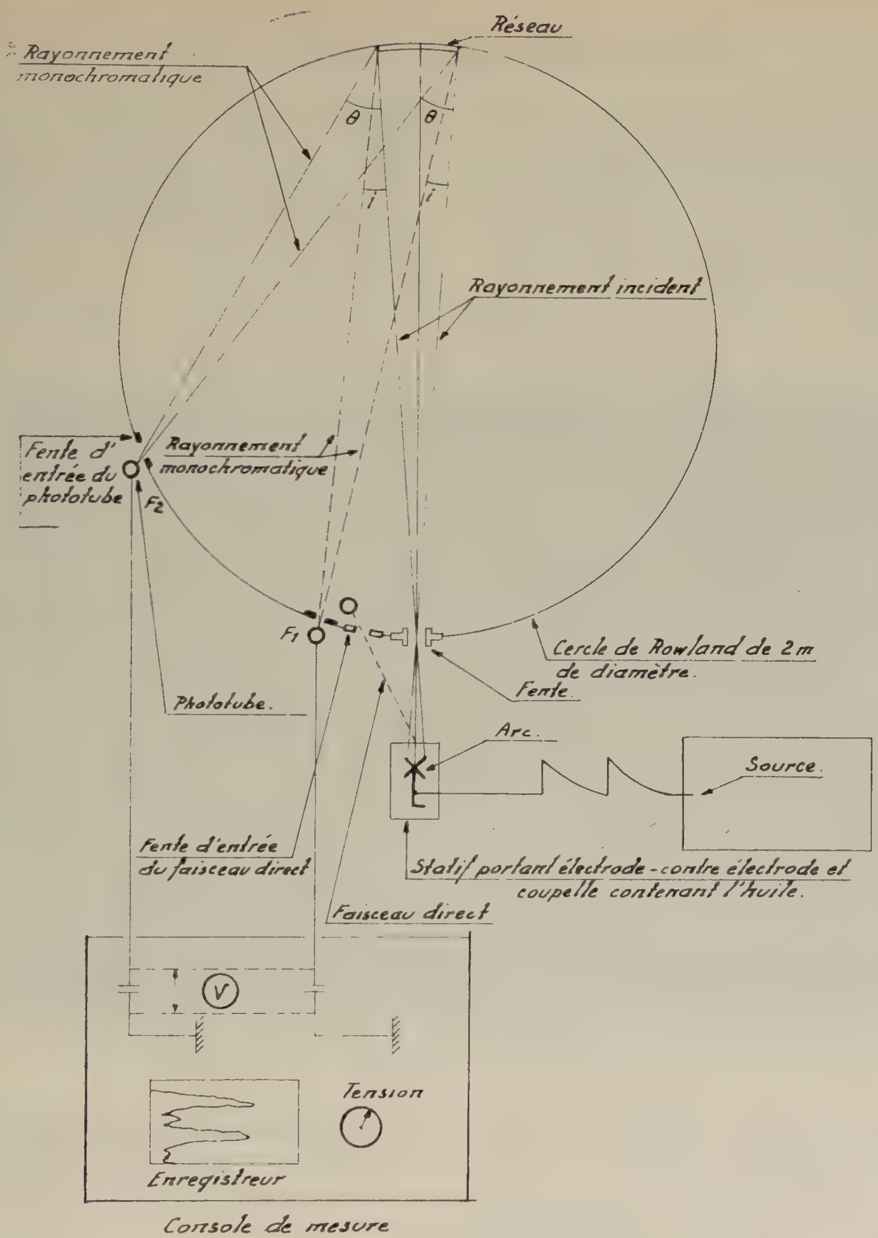

Fig. 6. — General arrangement of spectrographic equipment.

Explanations of the French terms :

Source = power source. — Statif portant électrode, contre-électrode et coupelle contenant l'huile = stand carrying electrode and counter-electrode and the vessel containing the oil. — Cercle de Rowland de 2 m de diamètre = Rowland circle of 2 m diameter. — Fente = slit. — Réseau = grating. — Rayonnement incident = incident radiation. — Rayonnement monochromatique = monochromatic radiation. — Fente d'entrée du phototube = phototube inlet slit. — Fente d'entrée du faisceau direct = inlet slit for direct beam. — Faisceau direct = direct beam. — Console de mesure = measuring panel. — Tension = voltage. — Enregistreur = recorder.

3) isolate the characteristic spectrum lines to be measured, and convert their intensities into measurable values.

This programme is carried out by means of three different parts of the spectrographic equipment :

1) the « source » or spark generator which excites the atoms by applying to the terminals of two electrodes a damped spark;

2) the « spectrograph » proper which serves to decompose the spectrum produced by the oil and by the particles suspended in it into monochromatic radiations;

3) the « measuring equipment » which isolates the characteristic spectrum lines and measures their intensity.

Figure 6 shows schematically the whole of this apparatus, whilst figures 7, 8 and 9 show photographs of source, spectrograph and measuring panel, respectively.

If we follow figure 6, we find that the spark produced by the source is applied to the electrodes which are placed on the spectrograph. The organs carrying the electrodes and the sample to be analysed are jointly called the « stand ».

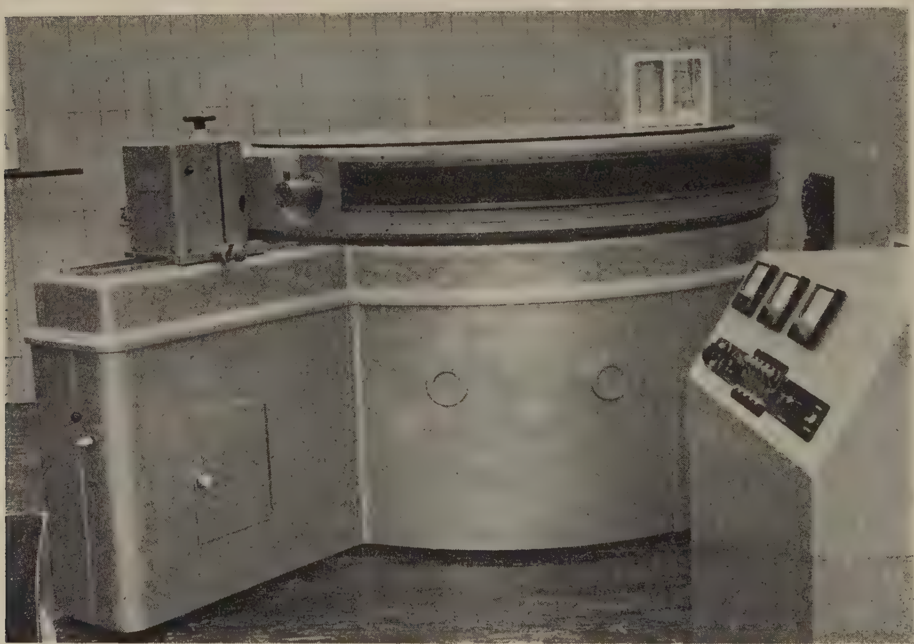

Fig. 7. — View of spectrograph and source.

The radiations produced enter the interior of the spectrograph through the inlet slit and are diffracted into monochromatic radiations by the grating. Each of the nine radiations selected for measurement acts on a photomultiplier

tube which transforms the incident radiation into an electric current, amplifies this current, and sends it to a measuring bridge consisting of condensers. The voltage at the terminals of the latter is raised, and eventually transformed into readings.

The source has a dual function :

1) to produce, at will, arcs or sparks with characteristics suitable for the analytical problem;

2) to stabilize the spark chosen, irrespective of any variations of the external supply.

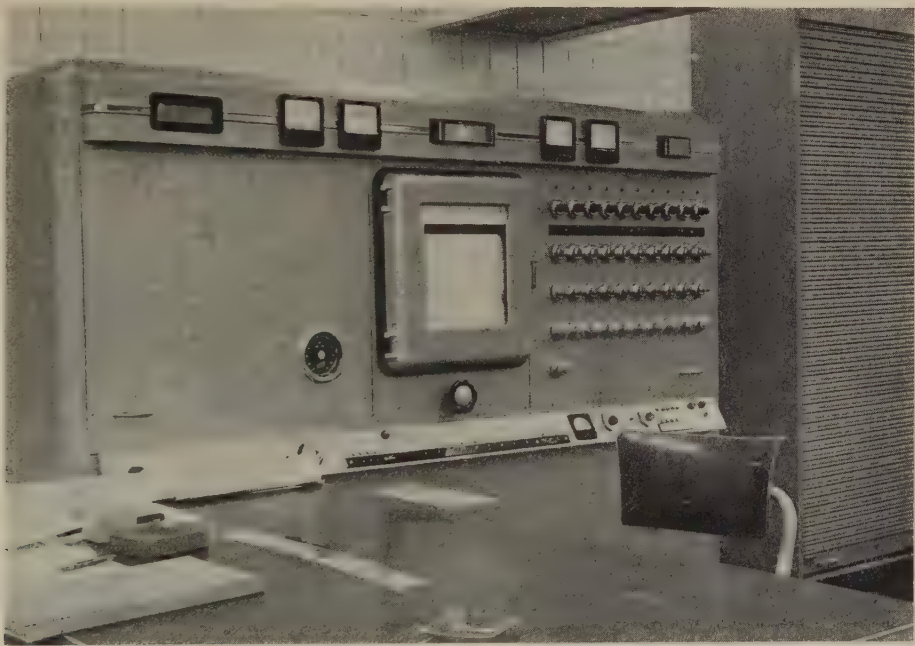

Fig. 8. — View of measuring panel.

In the following paragraphs, we shall examine each of the constituent parts of the equipment in turn.

3.2.2. *Source.*

The radiations emitted by the oil depend on the excitation condition of the atoms. As this condition is brought about by a succession of sparks, the latter must be perfectly stable if the spectrum emitted is to be invariable.

Messrs. M.B.L.E. have adopted a thyratron controlled generator (Macq licence) of Belgian design and manufacture, with the following principal characteristics :

1) the power discharge is initiated by means of an electrode gap ionisation system;

2) the power spark is provided by the discharge of a system of condensers;

3) stability of discharge is ensured by a regulating system.

The whole arrangement is shown in figure 10 in the form of a block diagram.

Ionisation circuit and power circuit are applied to the terminals of the electrode gap. A condenser, series-connected in the ionisation circuit, prevents any interference between the two circuits. The regulation circuit acts on the grid of the power thyratron as a servo-mechanism.

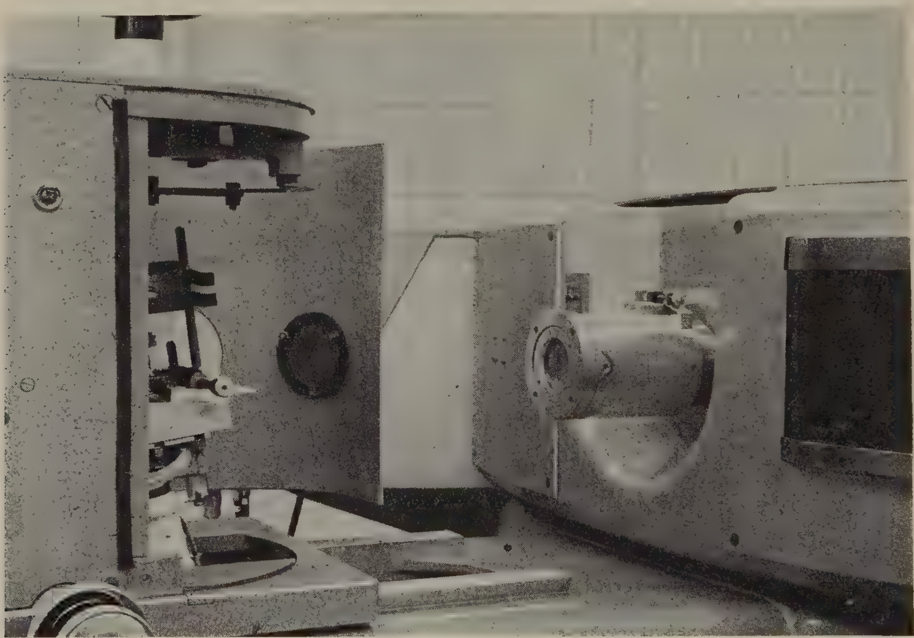

Fig. 9. — View of stand and inlet slit of spectrograph.

3.2.2.1. *Ionisation circuit.*

This circuit is shown in figure 11. Condenser C_1 is charged to a peak voltage of 10 kV through a transformer T_1 and a diode R_1. This condenser can only be discharged through the auto-transformer T_2 and condenser C_2 if the grid of thyratron T_1 is brought to a positive potential in relation to the cathode.

A normal type electronic circuit transmits, during each current alternation, a positive peak of 250 V to the grid of this thyratron which is energized and enables the condenser C_1 to be discharged in the electrode gap.

3.2.2.2. *Power circuit.*

The power circuit is shown in figure 12.

A thyratron T_2 fed by a mains transformer serves to charge the condenser C. The phase difference of the impulse applied to the thyratron grid in rela-

tion to the mains voltage is controlled by the regulating and control circuit in such a way as to keep constant, either be obtained by combining, either by means of keys or electro-magnetically by means of push-buttons, the different

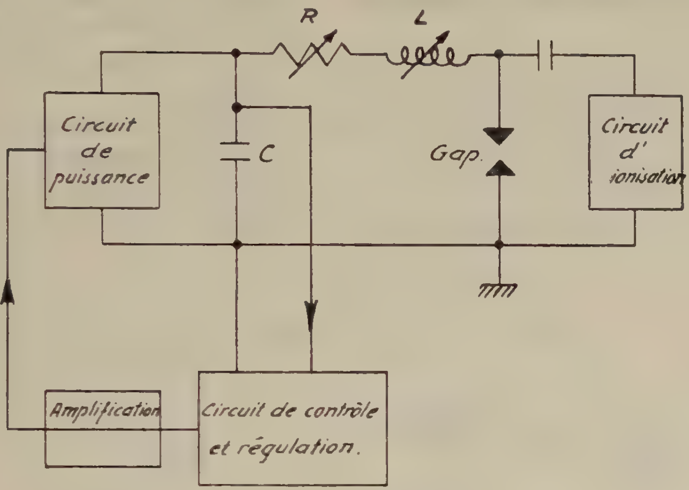

Fig. 10. — Block diagram of spectrographic equipment.

Explanations of the French terms :

Circuit d'ionisation = ionisation circuit. — Circuit de puissance = power circuit. — Circuit de contrôle et régulation = control and regulating circuit.

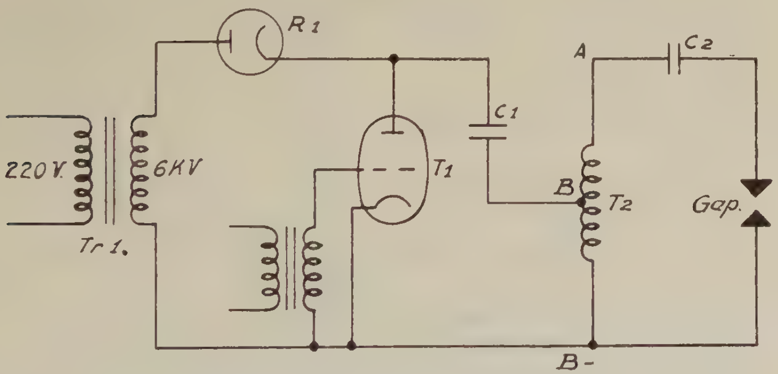

Fig. 11. — Diagram of ionisation circuit.

the maximum voltage at the terminals of the condensers, or their discharge current.

The different values of R, L, C can resistances, chokes and capacitances according to the analysis programme to be followed.

Figure 13 shows, on the basis of the

sector voltage, the different voltages affecting the ionisation and power circuits.

Figure 13*b* shows the sinusoidal voltage of the sector.

The voltage of the analytical condenser C varies as shown in figure 13*c*. The charge of this condenser is controlled by the impulse of the grid voltage of power thyratron T_2 shown in figure 13*a*. At this moment, the condenser is charged as shown in 13*c*. The variation of the condenser current is shown in figure 13*d*.

The discharge of the capacitance shown in figures 13*c* and 13*d* is controlled by the ionisation circuit. The pilot impulse is shown in fig. 13*e*.

To ensure that the charging current, and hence the discharge current, of C is constant irrespective of external conditions, the grid voltage of thyratron T_2 controlling the charge of C has a phase lag, so arranged that the sector voltages are corrected. For this purpose, it is sufficient to shift point A in relation to the phase origin. For example, if the sector voltage drops, point A approaches the origin so that the corresponding voltage variation is corrected (fig 13*a*).

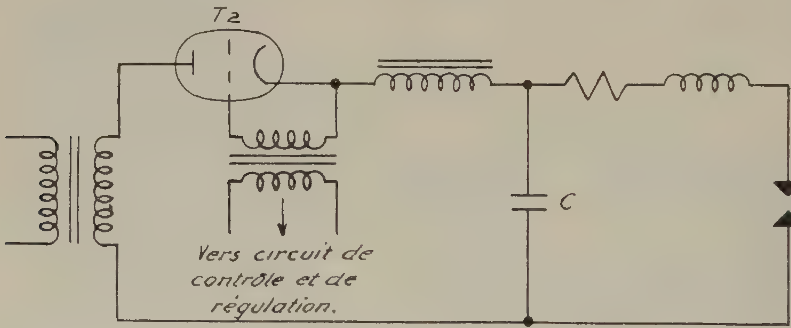

Fig. 12. — Diagram of power circuit at source.

Explanations of the French terms :

Vers circuit de contrôle et de régulation = to control and regulating circuit.

3.2.2.3. *Regulating and control circuit.*

Figure 14 shows the regulating and control circuit.

Block A F represents an electronic circuit which transforms the sector current into an impulse at industrial frequency.

The positive impulse acts on the grid of tube T_3. T_3 and T_4 jointly form an auto-stable circuit, functioning as follows.

The positive impulse on the grid of T_4 brings the tube to saturation; at that moment, the potential of point B is at a minimum. The negative impulse thus produced is transmitted to the grid of T_4 across C_1 so that T_4 is blocked. At that moment, the voltage at point G is at a maximum.

T_3 and T_4 remain in this condition for a length of time which is governed by the time constant of the grid circuit of T_4 and the grid potential of T_4, i.e. point D. The width of the rectangular

impulse obtained at point G is thus a function of the variations of the grid potential of T_4.

The return to the rest position is voltages at the terminals of R_1 and R_2. The voltage at the terminals of R_2 is proportional to the current which passes in tube T_5. This current, in its turn, is

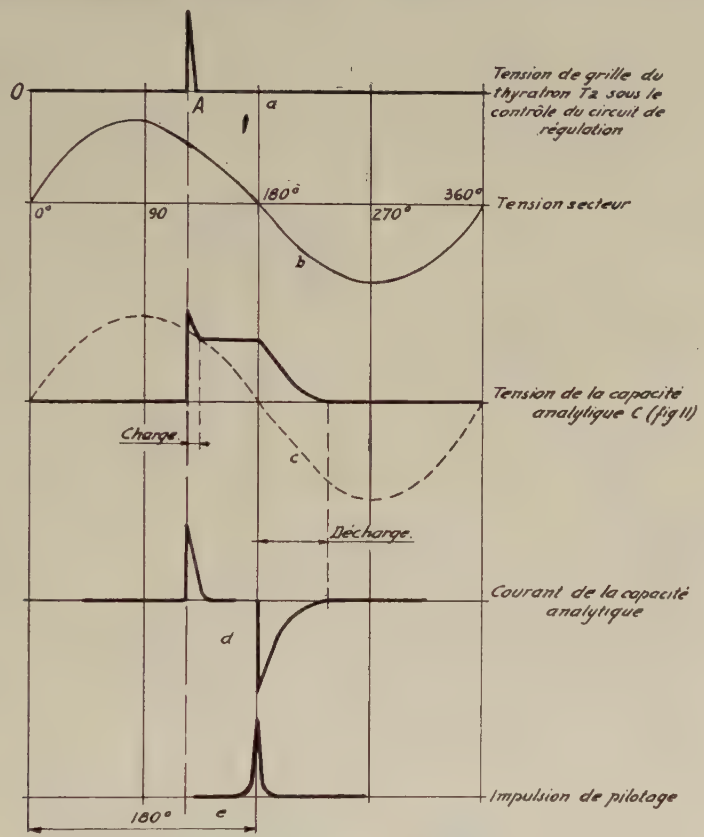

Fig. 13. — Producing the different voltages of the ionisation and power circuits.

Explanations of the French terms :

Tension de grille du thyratron (T2) sous le contrôle du circuit de régulation = thyratron grid voltage (T2) subject to the control of the regulating circuit. — Tension secteur = sector voltage. — Tension de la capacité analytique C (fig. 11) = voltage of analytical capacity C (fig. 11). — Courant de la capacité analytique = current of the analytical capacity. — Impulsion de pilotage = pilot impulse.

speeded up by the connection of the two tubes by means of resistance R_3.

The voltage at point D in relation to the mass is the sum of the apparent proportional to the peak voltage at the terminals of the analytical condensers C. The voltage at the terminals of R_1 is proportional to the sector voltage.

Figure 15 shows, in the same form as figure 13, the modifications of the signal at different points of the circuit.

Figure 15*a* shows the sector voltage (point A).

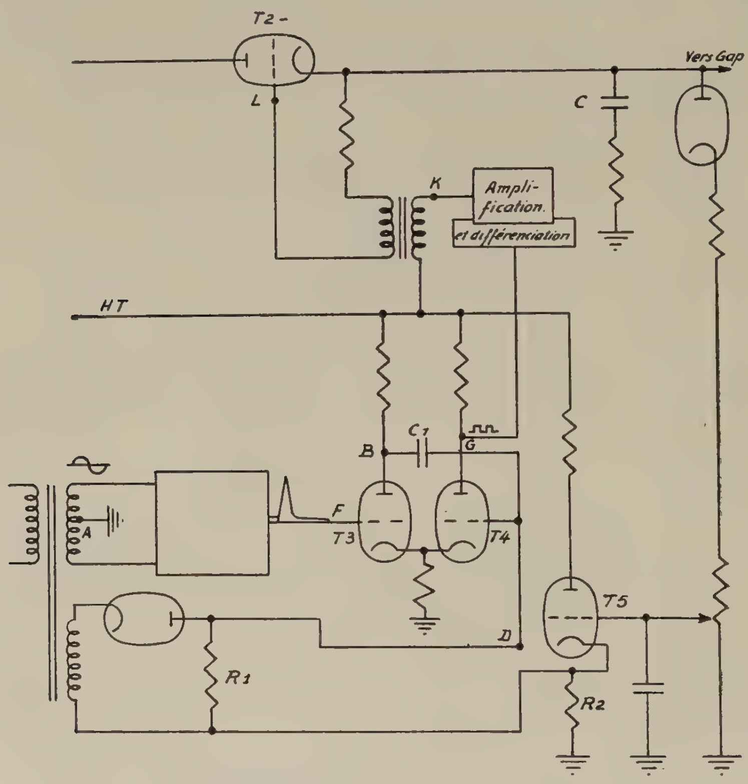

Fig. 14. — Diagram of regulating and control circuit.
N. B. — Vers gap = to electrode gap.

After passing to the electronic block A F, the sinusoidal input voltage is transformed into an impulse as shown in figure 15*b*.

T_3 and T_4 together produce the rectangular signal (fig. 15*c*) the length of which varies as explained above.

After passing to the amplification and differentiation block, the signal emerges at K as shown in figure 15*d*.

After passing to the transformer, the signal emerges at L and is applied to the grid of the thyratron of the power circuit. Figure 15*e* is identical with figure 13*a*.

In short, figures 15*a* to 15*e* explain how the variable signal 13*a* is obtained. Owing to this arrangement, the characteristics of the spark at the gap are independent of the fluctuations of the mains voltage provided that their amplitude does not exceed 10 %.

3.2.3. Spectrograph.

The spectrograph proper consists essentially of a circular body carrying the organs required for producing and the only means of decomposing a spectrum, using the variation of the refraction index as a function of the wave length.

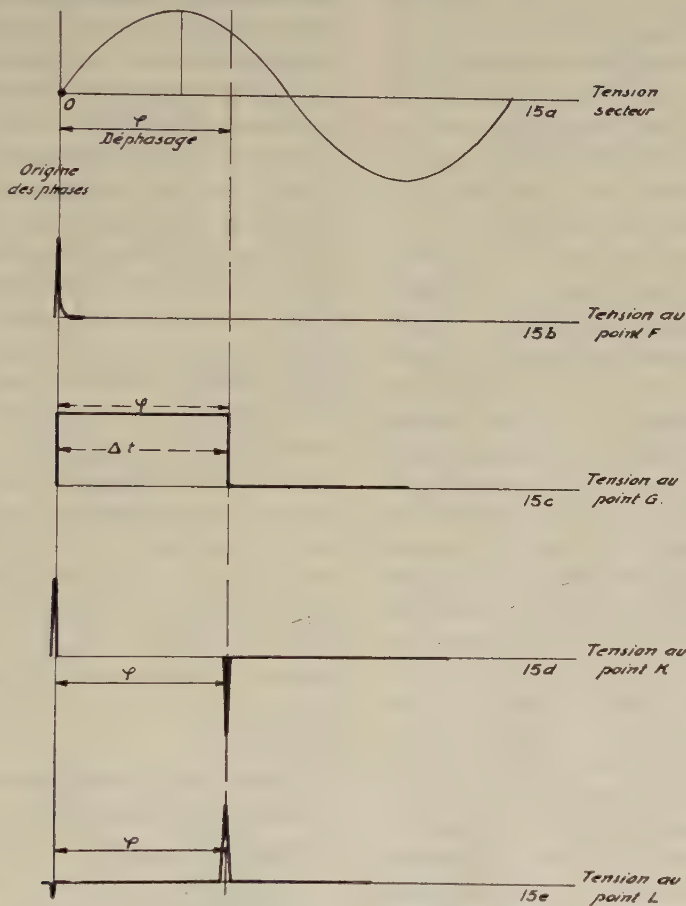

Fig. 15. — Producing the regulating signal acting on the grid of the power thyratron.

Explanations of the French terms :

Tension secteur = sector voltage. — Déphasage = phase displacement. — Origine des phases = phase origin. — Tension au point F = voltage at point F. — Tension au point G = voltage at point G. — Tension au point K = voltage at point K. — Tension au point L = voltage at point L.

decomposing the spectrum. It also carries the stand with the electrodes, the cupel and the phototubes.

Some ten years ago, the prism was

In modern practice, spectra are decomposed into their constituents by making use of the diffraction properties of gratings. A grating is obtained by en-

graving on a steel plate a series of parallel grooves. According to the type, a grating may include from 500 to 1 500 lines per mm. The interval between the lines is of the order of 1 micron the light projected on such grating is reflected and diffracted. The angle of reflection is a function of the wave length of the incident light and of the spacing of the lines of the grating.

Compared with the prism, the grating has the following advantages :

— the dispersion capacity is independent of the wave length of the light;

— the separating capacity of a good grating is superior to that of a prism.

The grating used for the spectrograph has been calculated by Professor Swings of Liège University, and manufactured by Bausch & Lomb. The original grating is engraved on steel. The spectrograph is equipped with a replica obtained from a casting of the original. The grating is concave, with a curve radius of 1 999.5 mm. Its length is 80 mm, its height 50 mm.

The grating carries 981.6 lines per mm. The original has been engraved by means of a diamond point. Parallelism and correct spacing of the lines must be ensured with a tolerance of 0.01 micron and are verified by means of the wave length of a sodium line. These few technical details show sufficiently that the manufacture of such gratings is up against considerable technical difficulties, and that the development of this technique is of comparatively recent origin.

In order to focus the diffracted spectrum, the Paschen-Runge arrangement is used which is shown in figure 6.

After passing the entry slit, the spectrum is reflected and diffracted by the grating. Each monochromatic line forms a given angle with the incident ray. This angle varies with the wave length of the radiation. The grating has a curve radius of approx. 2 m and is placed tangentially to a circle of 2 m diameter, known as Rowland's Circle and materialized by the spectrograph.

With this arrangement, all the rays of a given wave length are focussed on the Rowland Circle, irrespective of the point of incidence on the grating. This feature is illustrated in figure 6. At the focussing point, a micrometric slit is placed which is known as outlet slit and which isolates the spectrum line to be measured.

The great advantage of this arrangement is that it obviates the need for any supplementary optical focussing system, with the result that luminosity is improved.

For the record, we quote below the principal characteristics of the spectrograph.

Spectrograph :

Paschen-Runge arrangement.

Diameter of Rowland Circle : 2 m.

Grating :

Dimensions : 80 mm $\times$ 50 mm.

Number of lines : 981.6 per mm.

Curve radius : 1 999.5 mm.

Cutting angles : $11^{\circ}30'$ and 18°.

Resolving capacity : 75 % of 78.560 (theoretical maximum capacity).

Dispersion capacity : 4.8 Å/mm first order.

Due to these two cutting angles and a lighting following the normal direction,

this grating permits the use of two complete spectra : one on either side of the optical axis. At present, we are only using the left-hand side which has been equipped with an electronic camera with nine phototubes. Eventually, it will be possible to equip the right-hand side with a photographic or electronic camera according to requirements. This would permit the carrying out of an industrial programme and a research programme.

The inlet and outlet slits are, according to type, from 50 to 80 microns wide. The parallelism of the rims must be very good. The quartz slits with which the M.B.L.E. spectrograph is equipped are protected by patents and obtained by a photographic process followed by metallisation under vacuum.

3.2.4. *Measuring equipment.*

The measuring equipment consists of the phototubes placed in the body of the spectrograph at the outlet slits of the spectrum lines, and the measuring panel. To each of the elements to be measured corresponds one outlet slit and one phototube. Figure 16 shows the diagram of the charging circuit of the measuring condensers. This arrangement applies to one element, and must

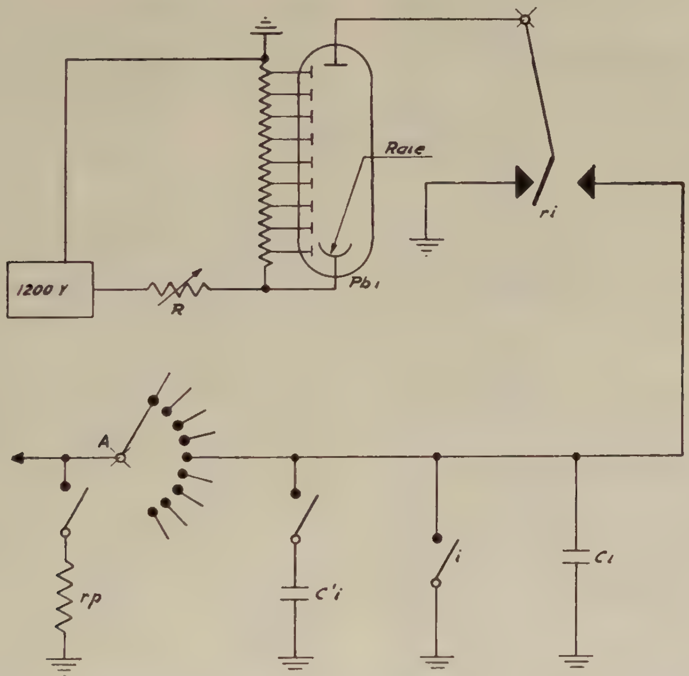

Fig. 16. — Diagram of the charging circuit of the measuring condensers.
N. B. — Raie = spectrum line.

be multiplied by the number of elements to be measured.

The phototubes, also known as photo-multipliers, consist of an anode, nine dynodes and one cathode. The cathode Ph (fig. 16) receives the radiation and voltage of the phototubes is regulated by means of an adjustable resistance.

The phototubes can sustain a maximum voltage of 1 200 V.

Condenser C is charged by the phototube current across a rocker contact r

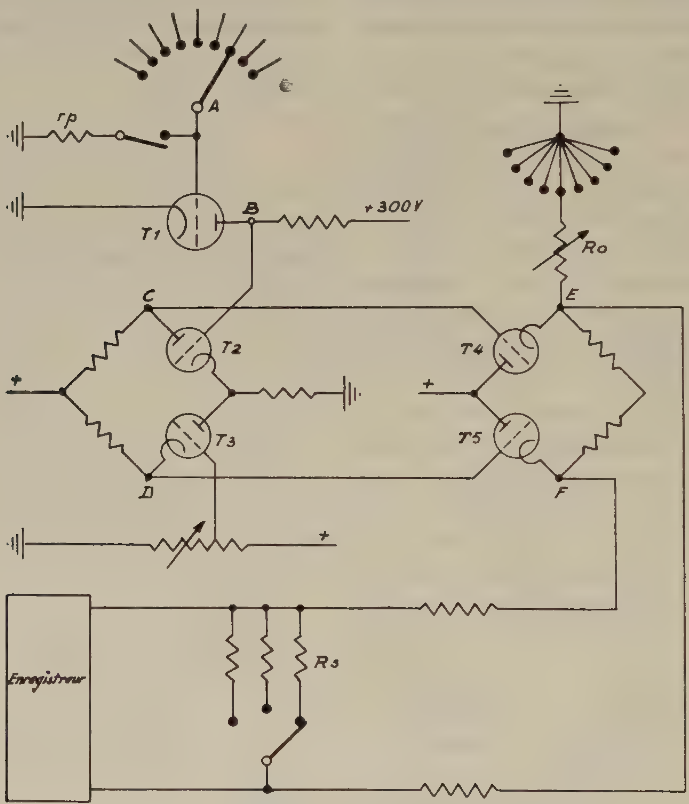

Fig. 17. — Basic diagram of measuring bridge.
N. B. — Enregistreur = recorder.

transforms the incident photons into an electronic current. This current is very small, of the order of 10^{-13} amps, and is amplified by the nine dynodes about 1 million times. The positive pole is connected to the mass, and the negative pole is at a negative potential. The which connects the anode with the mass when the spectrograph is not working. In this way, the quiescent current discharged by any phototube when at rest does not charge the measuring condensers. Contact *i* connects the condenser C to the mass so that the read-

ings are effaced before a fresh analysis is commenced.

The charging current raises the voltage of the condensers C to between 1 and 15 V. If the charging current is too intense and the voltage of 15 V is exceeded, condensers C′ can be parallel-connected with C so that the measuring scale is doubled.

A selector device at point A applies the voltage of the ten groups of measuring condensers one by one to the measuring bridge proper.

Measuring bridge.

There are two systems which can be used indifferently : the vibrating condenser and the electrometer. In the following, we shall only describe the second method.

The diagram of the measuring bridge is reproduced in figure 17. It consists essentially of a two-stage amplifier with symmetrical Wheatstone bridge connection to compensate the variations of the sector voltage in the tubes.

The diagram has been deliberately over-simplified by leaving out technological details, in order to make the exposition clearer.

Departing from point A, which is identical with point A in figure 16, the voltage taken from the measuring condenser *Ci* is applied to the grid of an electrometer triode T_1. Point B is connected, firstly with the anode and, secondly, with the 300 V voltage across a resistance. The voltage at point B will be variable and will depend on the voltage drop in the resistance. This voltage drop is a function of the current which passes through T_1, and thus of the grid voltage which is equal to the charge voltage of the measuring condensers. A first Wheatstone bridge consists of two resistances and two tubes, T_2 and T_3. The grid of T_2 is connected to the voltage of point B, and the grid of T_3 is connected to a variable resistance. Its potential can therefore be regulated.

The grids of tubes T_4 and T_5 of the second Wheatstone bridge are connected to the voltages of points C and D of the diagonal of the first bridge.

Points E and F of the diagonal of the second bridge are connected to the recorder. The variable resistance R_0 serves to regulate the zero point of the bridge. The resistances RS which shunt the recorder serve to vary the sensitivity of the bridge.

Resistance *rp* placed before triode T_1 serves for the adjustment of the outlet slits. By connecting the measuring condensers to the mass across that resistance, the condensers are prevented from being charged, and the current discharged by them permits the adjustment of the outlet slits.

The measuring panel carries three series of ten regulating buttons, viz. nine for the elements and one for the direct beam.

The first series serves to adjust the voltage of the phototubes and acts on the resistances R of figure 16.

In order to increase the flexibility of the apparatus, each phototube is associated with two sets of regulating potentiometers (RS), each of them known as a measuring channel.

The second and third series of buttons are each connected to one channel.

In view of the fact that the zero point and the sensitivity of the bridge must be separately regulated, each button has a dual function, due to a coaxial system of control.

A switch permits the choice of any of the measuring channels as may be required for each element individually.

The measuring panel also carries the transformers required to feed the different parts of the equipment with the desired voltage, as well as the main circuitbreakers, the different voltmeters, etc.

3.4. *Description of the air conditioning installation.*

3.4.1. *General.*

The spectrographic equipment is mounted in a cellar of approx. 4 m width and 10 m length.

This arrangement has been adopted in order to guard the equipment as effectively as possible against the seasonal and daily temperature fluctuations and to render the air conditioning system as efficient as possible.

The dispersion of the spectrograph is 4 Å per mm i.e. each interval of 1 mm measured on the Rowland circle of 2 m diameter corresponds to a variation of the wave length by 4 Ångströms. The slits placed at the outlet points of the monochromatic lines to be measured have a width of 50 microns. As a result of temperature fluctuations the outlet slits may be shifted so that they are no longer exactly at the outlet points of the spectrum lines; which causes a systematic measuring error. A movement by a few microns is sufficient to falsify the readings completely. The temperature must be controlled in such a way that the total deviation does not exceed ± 1/4° C, it being understood that these fluctuations must be slow and that the mean temperature must be strictly constant.

Moreover, the phototubes are highly sensitive to the degree of humidity of the air. The deviation of the degree of humidity must not exceed ± 5 %. Furthermore, the air must be free from dust which may reduce the luminosity of the grating and jeopardize the proper working of the electronic equipment.

In order to obtain such conditions, the premises have been air-conditioned by means of an installation supplied by Chrysler Airtemps.

3.4.2. *Air conditioning installation.*

The conditions of temperature and relative humidity at the laboratory are as follows :

Temperature : 22° C ± 1/4° C.
Relative humidity : 50 % ± 5 %.

These conditions have been chosen so as to ensure congenial working conditions for the personnel working the equipment.

In order to adhere to such exacting tolerances, the equipment comprises :

1) an electric heating battery;

2) a freon cooling battery;

3) an air desiccator set;

4) an air humidifier set.

An electronic regulator permits casc-

ade switching to five positions : two cooling positions, and three heating positions.

An amplifier is connected to the sensitive probing devices which are mounted on the premises and act as thermostats.

These devices, numbering two, consist of resistances inserted in a measuring bridge connected to the grid circuit of a pentode.

Each of the five electronic relays corresponds to a given variation of the probers and controls the corresponding part of the air-conditioning set.

Two hygrostats, one for the lower limit and one for the upper limit, act on the apparatus which serves to keep the relative humidity within the described limits.

In order to comply with the conditions imposed and to reduce the detrimental influence of the phenomenon of inertia which would prevent adherence to these limits, a very large volume of air circulates in the laboratory. The air is distributed by diffusors so as to protect the staff against troublesome draughts and air currents.

The air distribution is complicated by the fact that the cellar has a very low ceiling (approx. 2 m) and that the circulation is hindered by heavy reinforced concrete girders.

Dust removal is ensured by means of an electrostatic filter which consists essentially of :

1) ionising tungsten wires, suspended between the ionisation plates;

2) collector plates of aluminium;

3) a secondary filter of the dry type which has a triple function, viz. :

a) to equalize the flow of air over the whole section of the filter;

b) to stop the drops of water when the collector plates are washed;

c) to serve as auxiliary filters if the electrostatic filter should fail;

4) a water distribution system for the periodic washing of the collector plates so that the dust is removed;

5) the feeder box.

The dust particles suspended in the air assume a positive charge when passing over the ionisation wires connected to 8 000 V D.C.

These particles are removed on the collector plates.

After some teething troubles due to the very exacting specifications imposed on the manufacturer, the equipment works to complete satisfaction.

To our cost, we found that if the temperature deviation exceeds $\pm$ 1/4° C, the slits are no longer in their correct position and the results recorded can no longer be used because of the scatter of the readings.

In view of the importance of regulating the temperature and the relative humidity of the air, this question is regarded as sufficiently interesting to warrant a brief exposition of the solution adopted by us.

4. Description of the method of analysis and measurement of the degree of repeatability.

In this chapter, we shall examine the different operations required to carry out an analysis, from the taking of the sample to the measuring of the concentration.

4.1. *Sample-taking.*

Sampling might seem to be a routine operation. It is, however, probably the most delicate operation of all, because it is on the sampling that the effectiveness of the method depends. The taking of the samples must be standardized in such a way that it is possible to compare the samples taken at different times from the same locomotive. Owing to the multiplicity of depots to which the locomotives are allocated and, consequently, the great number of operators, a control of the sample-taking procedure is difficult.

The programme of operations described below entails the greatest possible guarantee for the standardization of sampling.

This programme is based on the following conditions :

1) the sample must be taken when the engine is warm and idling;

2) the sample must be taken by means of a special sampling cock located on the oil return line between the crankcase and the oil filter. The sample must only be taken after 1 l of oil has been allowed to run off;

3) the cans containing the oil are not recovered after the analysis in view of the fact that the cost of cleaning them is higher than that of emptying them, and that the risk of a fresh sample being polluted by traces of residue from a previous sample must be avoided at all costs.

In the case of main line locomotives, samples should be taken after each servicing period, i.e. every 8 to 10 days. The sample will arrive at the laboratory the day after it has been taken, and will be analyzed on the third day. This method has been found satisfactory, and spot tests have shown that the programme is adhered to by the various depots. In the case of shunting locomotives and railcars, samples are taken at intervals of two months.

4.2. *Preparation of the sample.*

The sample is prepared in accordance with the American ASTM standards. The can containing the oil is :

1) heated to a temperature of 60° C;

2) mechanically stirred for 15 min;

3) filtered through wire netting with a mesh of 125 microns side length;

4) stirred again for 5 min.

The oil is then placed in an aluminium vessel; each sample is prepared in duplicate. Experimentally, a number of vessels have been provided with an interior lining of silicone in order to avoid the risk of inter-action between the aluminium of the cupel and the oil. The two types of cupels were found to yield identical results.

4.3. *Analysis conditions.*

The analysis is carried out by means of direct combustion of the oil in the cupel, using the rotating electrode method. The cupel is placed on the spectrograph stand. The electrode consists of a graphite disk of 5 mm width which dips into the cupel and carries the oil, through its rotation, to the counter-electrode. The electrode rotates at a

constant speed of five revolutions per minute.

The cupel contains 1.5 g of oil.

The sparking conditions are as follows :

Power source settings : C 27;

Pre-sparking time : 10 sec;

Arcing time : 40 to 50 sec.

The counter-electrode consists of a graphite rod of 6.35 mm diameter.

In order to ensure a good repeatability of the readings, the disk carries out a complete rotation before the presparking begins.

The arcing time is controlled by the direct-beam method which is as follows :

In the body of the spectrograph (cf. fig. 6), a micrometric slit has been cut out. Behind this slit is placed a phototube which receives directly the whole of the radiations emitted by the arc, hence the name direct-beam method. This phototube is connected to the measuring condensers which integrate the luminous flux received by the phototube. The condensers are so rated that saturation is avoided, and the voltage at their terminal is proportional to the time integral of the luminous flux.

When the pre-determined voltage has been attained, the arc is cut out automatically. In spite of the stabilisation ensured by the power source, the arc is not strictly constant and the arcing time will vary so as to preserve the integral of the luminous flux. By means of a selector switch located on the measuring panel, the operator is able to vary the voltage at which the arc is cut out by the direct beam condensers. It is thus possible to vary the arcing time while all the other factors remain unchanged. It must be understood that such a modification calls for the recalibration of the curves which we shall discuss later on. In fact, we have adopted arcing conditions suitable for the problem to be solved, and we shall take care not to modify them.

The direct-beam method can only be used for the analysis of liquid solutions with very small concentrations. In this case, the luminous flux which acts on the phototube of the direct beam will only depend on the total quantity of light emitted by the oil. As the active elements occur in very small concentrations, the variations of their concentration have no influence on the total quantity of light emitted.

Let us assume two samples : one with a low concentration, say 100 p.p.m. of active matter, the other with a high concentration, say 400 p.p.m. In the former case, the elements to be measured represent no more than on ten-thousandth, in the latter case four ten-thousandths of the weight of the oil. The presence of these elements will have no influence on the total light emitted by the arc. In metallurgy, this method cannot be used because the relative concentration of the elements to be measured is not negligible in relation to the main constituent, and an internal standard must be used.

4.4. *Measuring the concentration.*

The measuring panel carries an electrometer which measures, for each element, the voltage at the terminals of the corresponding condensers.

This voltage is a function of the concentration of the element and of the arcing time. In fact, as has been mentioned in the preceding chapter, every phototube discharges a quiescent current which is superimposed on the current produced by the element, so that the deviation of the electrometer is a function of the concentration of the element to be measured and of the quiescent current produced by the phototube. As the latter is a function of the arcing time, the deviation of the electrometer will differ if two analyses of the same sample are carried out in different times.

The relation which governs the three variables : arcing time, concentration, and deviation of the electrometer must be graphically plotted for each element.

We shall establish the corresponding equation, taking into account that we are using the direct-beam method as internal standard.

We shall use the following notations :

N_i : the quiescent current of the phototube of element i, expressed in units of deviation of the measuring bridge per second;

N_o : the quiescent current of the phototube of the direct beam;

Δ_i : the total deviation of the electrometer for element i of concentration C_i;

C_i : the concentration of element i;

t_i : the sparking time expressed in seconds.

The charging current of the condensers for element i is proportional to $C_i^{m_i}$ where m_i is an exponent depending on the apparatus and the nature of the element measured.

The total deviation of the electrometer is the sum of the deviations due to the quiescent current of the phototube i.e. $N_i t_i$, and of the element $k_i C_i^{m_i}$.

We thus have :

$$\Delta_i = N_i t_i + k_i C_i^{m_i} \qquad (1)$$

The charging current of the reference phototube is proportional to the time integral of the luminous flux plus the quiescent current of the phototube.

The deviation of the measuring bridge is always equal to 100 partitions.

We thus have :

$$a \int_0^{t_i} \Phi \, dt + N_o t_i = 100 \qquad (2)$$

By dividing (1) by (2), one obtains :

$$\frac{\Delta_i}{100} = \frac{k_i C_i^{m_i} + N_i t_i}{a \int_0^{t_i} \Phi \, dt + N_o t_i} \qquad (3)$$

or

$$\Delta_i = 100 \frac{k_i C_i^{m_i} + N_i t_i}{a \int_0^{t_i} \Phi \, dt + N_o t_i} \qquad (4)$$

For a given sample, the term $k_i C_i^{m_i}$ is constant so that, by substituting

$$k_i C_i^{m_i} = r_i$$

one obtains :

$$\Delta_i = 100 \frac{r_i + N_i t_i}{a \int_0^{t_i} \Phi \, dt + N_o t_i} \qquad (5)$$

If $N_o t_i$ is negligible compared with $a \int_o^{t_i} \Phi \, dt$ one can write :

$$a \int_o^{t_i} \Phi \, dt = 100$$

and equation (5) is reduced to :

$$\Delta_i = r_i + N_i t_i \qquad (6)$$

To determine the slope of the phototube, the procedure is as follows :

Samples of pure oil are measured, noting the deviations of the electrometer and the corresponding periods of time. The points thus obtained are plotted on a chart with the co-ordinates Δ_i and t_i. In keeping with the theory, the points form a straight line.

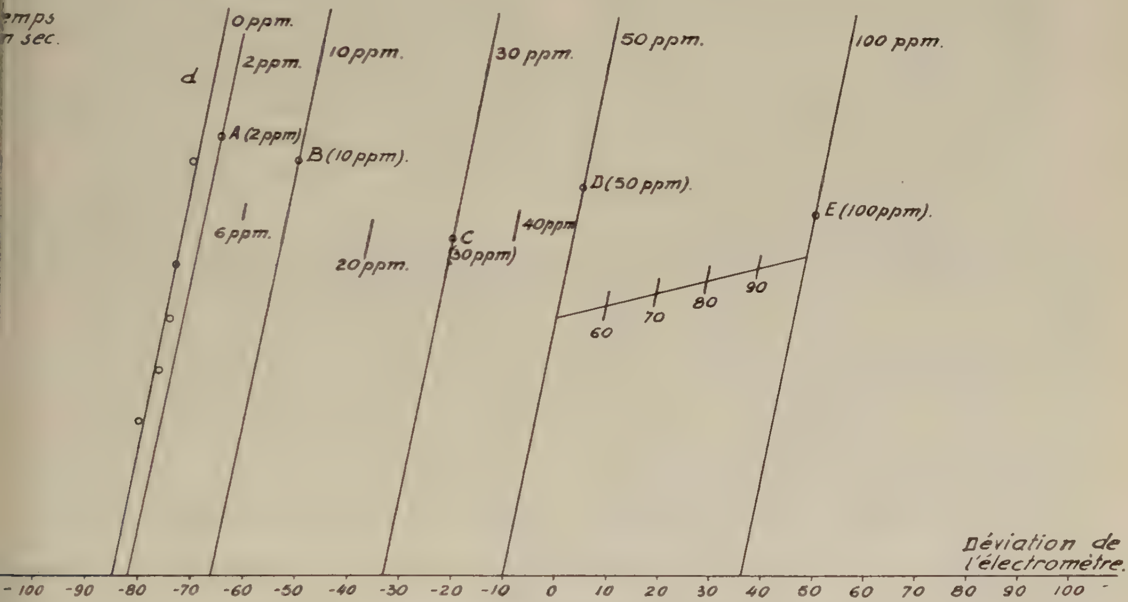

Fig. 18. — Construction of straight-line calibration curves.

Explanations of the French terms :

Abscissa : deviation of the electrometer. — Ordinate : time in seconds.

This is the equation of a straight line.

The slope of this straight line is a measurement for the quiescent current of the phototube, and that is why one talks of the slope of a phototube when wishing to express its quiescent current.

Measurements carried out with the spectrograph have shown that $N_o t_i$ is negligible compared with 100, and that equation (6) is valid.

In view of the fact that the slope of this straight line is independent of the concentration C_i of the element considered, any straight lines passing through points corresponding to other concentrations will be parallel to that straight line. As the relation between the concentration C_i and the deviation Δ_i is not linear, it is necessary to use several standard samples of known concentration in order to find

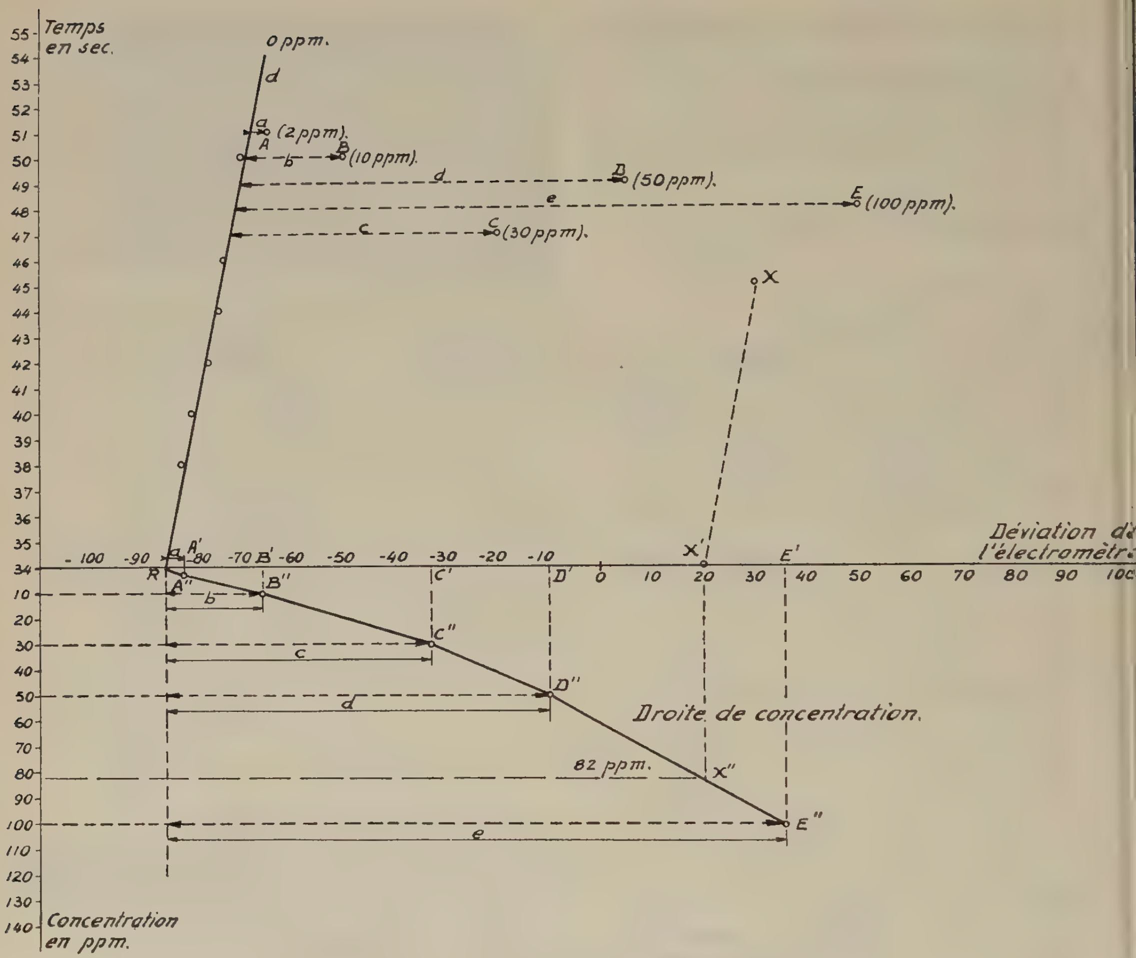

Fig. 19. — Construction of concentration line.

Explanations of the French terms :

Abscissa : deviation of the electrometer. — Top ordinate : time in seconds.
Bottom ordinate : concentration in parts per million.
Droite de concentration = concentration line.

the straight lines of concentration. For each element, we have five standards suitably staggered which permit easy interpolation. Each of the standards contains the nine elements so that the number of standard analyses is confined to five.

For each element, a chart similar to that of figure 18 is prepared. This particular chart has been determined for iron.

These concentration lines must be checked and rectified daily because :

— the slope of the phototubes, and

thus the slope of the lines, may vary, and

— the zero point of the measuring bridge may shift.

Moreover, if it is necessary to carry out daily a great number of analyses, the interpolation on the chart (fig. 18) is a laborious job.

We have worked out a method which obviates the need for determining the concentration lines except, of course, the reference line which shows the slope of the phototube. This method consists in determining the concentration line as a function of the deviation Δ_i for a given sparking time.

Before explaining this method, we should like to revert to equation (4) and to examine the law which represents the relationship between the concentration C_i and the deviation Δ_i if the sparking time is constant.

If t_i is constant, we can substitute $N_i t_i = d_i$

As we know that $a \int_o^{t_i} \Phi \, dt$ is equal to 100, we can write

$$\Delta_i = k_i C_i^{m_i} + d_i \qquad (7)$$

Equation (7) is the equation of a parabola, the order of which depends on the exponent m_i. In the special case of $m_i = 1$, (7) becomes a straight line; but m_i is generally different from 1.

In order to determine the concentration curve for a constant time, the procedure is as follows :

The chart is divided into two parts, with a common abscissa indicating Δ_i (cf. fig. 19). The upper ordinate represents the time t_i and the lower ordinate the concentration in p.p.m.

The reference line « d » is determined from samples of pure oil as for the chart (fig. 18).

In the top part of the chart are also plotted the five standard samples, viz. A, B, C, D and E.

One adopts a minimum time which is always observed when actual sample analyses are taken. For the plotting of the chart, it is convenient to let the zero point of the upper ordinates coincide with that time. In the example shown, this time is equal to 34 sec. The reference line « d » intersects the abscissa at the point G. As the reference lines passing through A, B, C, D and E must be the parallel to « d », they intersect the abscissa at the points A′, B′, C′, D′ and E′ obtained by marking the distances from G equal to the horizontal distances of the points A, B, C, D and E from the straight line « d ». The corresponding abscissae represent the deviation Δ_i for a constant sparking time of 34 sec. The concentration curves are plotted by projecting the points A′, B′, C′, D′ and E′ to A″, B″, C″, D″ and E″, i.e. parallel to the ordinate to the point of intersection with the corresponding concentration.

Line « c » shows the concentration as a function of the electrometer reading for a sparking time of 34 sec.

This chart can be used very simply in the following way :

Let us assume that a reading yields point X in the top part of the chart (fig. 19). X is then projected parallel to « d » to point X′ on the abscissa,

Sample No.	*Iron very high amount in p.p.m.*	*Iron high amount in p.p.m.*	*Boron low amount in p.p.m.*	*Copper standard amount in p.p.m.*	*5 elements together very high amount in p.p.m.*
1	230	65	20	31	582
2	204	63	18	31	544
3	200	58	18	31	711
4	206	63	18	30	621
5	210	60	17	31	692
6	202	60	18	36	619
7	202	62	16	26	634
8	210	63	18	29	606
9	212	62	19	32	559
10	200	58	17	27	662
11	206	65	18	31	692
12	196	68	18	35	765
13	214	61	17	30	635
14	194	63	20	29	578
15	216	62	18	30	581
16	198	65	18	33	581
17	208	65	16	32	711
18	210	55	17	29	606
19	186	63	18	25	663
20	202	65	20	30	627
21	208	67	18	33	661
22	210	64	20	31	733
23	214	54	17	34	664
24	202	57	19	29	615
25	196	60	18	26	656

Sample No.	*Iron very high amount in p.p.m.*	*Iron high amount in p.p.m.*	*Boron low amount in p.p.m.*	*Copper standard amount in p.p.m.*	*5 elements together very high amount in p.p.m.*
26	206	62	18	31	649
27	206	62	17	26	623
28	188	61	17	31	684
29	214	56	18	30	671
30	210	55	17	27	655
31	196	76	20	29	695
32	242	55	17	34	660
33	216	66	18	29	599
34	212	58	18	30	664
35	202	61	17	34	662
36	212	77	19	30	622
37	214	65	21	27	678
38	222	59	17	25	598
39	260	57	17	32	647
40	208	58	17	32	626
$m = \frac{Ex}{n}$	209	62	18	30	643
σ	13.13	4.9	1.4	2.7	43.7
σr	5.3 %	7.9 %	6.5 %	9 %	6.8 %
J	26.26	9.8	2.8	5.4	97.4
Jr	10.6 %	15.8 %	13 %	18 %	13.6 %

Fig. 20. — Measures of repeatability of spectrographic analyses.

and this point in turn is projected parallel to the ordinate on the curve « c ». The lower ordinate will then show the concentration in p.p.m.

Compared with, the conventional method, this graphic method has two advantages :

1) the correction of the reference

line « d» is easy as it is necessary to correct one line only. If one uses the network of reference lines, the graph must be completely re-drawn if reading is to be made easy;

2) for the purpose of quantification measurements on an industrial scale, the reading of the concentration on line « c » is quicker and more accurate than the interpolation between the calibration lines (fig. 18).

4.5. *Degree of repeatability.*

None of the considerations put forward in the course of this article would be of any value if, by repeating the analysis of the same sample several times, the results were to present such a scatter that it would not be possible to draw any conclusions from them. We have already defined and explained how the best repeatability can be obtained.

In order to define the problem more closely, we shall call σ the root mean square deviation of the total population of samples measured, and σ_r the ratio of the root mean square deviation σ and the mean value of all the readings m, i.e. $\sigma_r = \frac{\sigma}{m}$.

The confidence interval at the level of 95 per cent is given by 2 σ. We shall represent it by

$$J = 2\sigma$$
$$Jr = 2\sigma_r$$

By running standard samples of known concentration and reliable homogeneity, we can measure the repeatability of the apparatus as we eliminate the deviations caused by the actual samples. By analysing the latter, we get a measure of the overall repeatability.

We have carried out several series of tests, each comprising 40 actual samples. The results obtained are plotted in figure 20 for two samples of iron, one of copper, one of boron, and one containing five elements.

We find that the relative dispersion varies between 5 and 9 % and can be regarded as very good.

For the record, it is estimated by ASTM that the rotating electrode method applied to a direct reading spectrograph may show a relative dispersion of 10 % calculated for all the contaminants.

By applying this method of calculation to a series of 40 samples where six elements have a measurable concentration, one obtains the following results:

— Mean concentration of all the six elements : 177 p.p.m.

— Dispersion calculated for all the six elements : $\sigma = 10.1$.

— Corresponding relative dispersion $\sigma_r = 5.8$ %;

— Confidence coefficient at 95 % $J_r = 11.6$ %.

Figure 20 shows the results for five elements totalling 643 p.p.m.

These results show that we can have confidence in the method of preparing the samples and in the method of analysis.

4.6. *Recording the results.*

As already mentioned, the interpretation of the results of the analyses is

based on the study of the progress of the concentration of metallic elements in the oil baths. To facilitate interpretation, the results are recorded on a « Cardex » index card.

There is one card for each engine, and the cards are grouped according to the type of locomotive.

the locomotive, date of analysis, viscosity and acidity of the oil, the concentration of the different metallic elements, the last inspection or maintenance service carried out at the home depot. Particulars are also entered of important unscheduled works such as the replacement of a piston or segment, and of

Sp.15/MA.22-33. B LABORATOIRE SALZINNES

Du 24 7 58 au

RESULTATS DES ANALYSES DE L'HUILE DES MOTEURS DIESEL.

ATZ FEO Engin 005

Marque d'huile R40

Moteur 55E91

1000 Kms		Engl.	Cendres		Spectranalyse PPM.										Travaux moteurs.	Dates	
B	T	50°C			Fe	Pb	Si	Al	Sn	Ag	Cr	Cu	B		Code	M	J
95	95	17	2,0	1602	30	30	30	5	9	0,5	0	72	-	261		8	5
95	95			1692	30	35	33	3	3	0	0	65	-	282	Remplacement élément filtre.	8	6
96	96			1940	43	48	30	2	15	0,4	0	175	-	310		8	9
97	97			1940	43	45	30	4	28	0,8	0	165	-	311		8	11
97	97				53	49	30	0	43	1	0	260	-	334	Remplacement du bain.	8	12
0	99			0	7	0	0	6	5	0	0	3	-	384		8	14
1	100			0	8	1	0	3	5	0	2	4	-	385		8	16
2	101	12°8		0	8	20	17	7	13	0,2	20	16	-	436		8	20
3					12	3	13	4	8	0	0	5	-			8	22
4					8	2	3	5	10	0,2	2	6	-			8	25
10					11	2	1	3	0	0	0	10	-		Remplacement élément filtre	9	3

Fig. 21. — Standard index card for the control of spectrographic analyses.

Explanations of the French terms :

Résultats des analyses de l'huile des moteurs Diesel = results of the analyses of the oil of Diesel engines. — Engin = motive power unit. — Moteur = engine. — Marque d'huile = brand of lubricating oil. — Cendres = ashes. — Travaux moteurs = work done on engine. — Remplacement élément filtre = filter change. — Remplacement du bain = oil change.

The card is so arranged that it contains all the technical information concerning the life of the engine. A specimen of such a standard card is shown in figure 21. For each spectrographic analysis, the following data are entered : the age of oil bath, total kilometrage of

interventions on the part of the laboratory and the results of such interventions.

At the bottom of each card, two riders indicate the date of the last analysis and the existence of an abnormal concentration. With this arrangement, it is pos-

sible to verify rapidly whether all the locomotives are regularly subjected to spectrographic control, and the attention of the staff is drawn to engines which must be specially watched.

4.7. *Conclusions.*

In the course of this chapter, the methods of sample taking and of analysis have been successively examined. By determining the degree of repeatability of the method adopted, the validity of this method has been confirmed. Finally, we have seen how the results are recorded on index cards in order to facilitate interpretation.

These different techniques have been developed and introduced during the past six months. The results achieved up to now give rise to the hope that we have overcome the main difficulties of the spectrographic technique, and that it will be possible to avoid the traps which are bound to be in the way.

The following chapter deals with the first results and with the data obtained from the spectrographic control. In most cases, these results have been obtained by verifying through an inspection of the engine any cases of obviously suspect concentrations. It is only through such inspections that it will be possible to determine the ranges of normal and abnormal concentrations. These inspections have already enabled us to collect information which will be commented upon in the next chapter.

5. **Results and information obtained by means of spectrographic analysis.**

5.1. *General.*

The spectrographic equipment was delivered in May 1958 and taken into operation in June. At the moment of writing, the laboratory has thus been in operation for about six months. Engine control was begun with the main line locomotives and was gradually extended to cover all the Diesel-powered vehicles, viz. :

— 95 main line locomotives;

— 112 shunting locomotives;

— 214 railcars.

All the engines mounted in main line and shunting locomotives are of the low speed type, and all the railcar engines of the high-speed type.

Although the results obtained so far are still fragmentary, and although it has not yet been possible to carry out the whole programme envisaged, the first results are encouraging and confirm the principles set out in the first two chapters of this exposition.

Up to the end of November, 1958, a total of 2 500 analyses were carried out. Thirty of them, i.e. 1.2 %, have given rise to special measures.

We shall briefly examine a few typical cases.

5.2. *Determining the concentration lines.*

The intervals between filter changes, oil changes, inspections or reconditionings are calculated in thousands of kilometres. The concentration lines will therefore be determined for the coordinates « p.p.m. » and « thousands of kilometres ». The two types of motive power units are called A and B.

On vehicles of type A, only one type of lubricating oil is used, whilst vehicles of type B use two kinds of lubricating

oil. In the latter case, we shall distinguish the vehicles by the indices 1 and 2, i.e. B1 and B2.

During the past six months, none of the locomotives has covered more than 100 000 km. It is therefore not yet possible to plot complete concentration curves.

To indicate the order of magnitude, we may state that the monthly kilometrage varies from 8 000 to 11 000 km with vehicles of type A, and from 11 000 to 16 000 km with vehicles of type B, according to the home depot.

The normal life of an oil bath varies between 60 000 and 100 000 km as far as type A is concerned. For B1, it has been fixed at 50 000 km; for B2, it is of the order of 100 000 km.

The interval between two inspections is around 400 000 km for type A, and 550 000 km for type B.

Filters are changed every 8 000 to 12 000 km.

If all the engines of one type are considered together, which can be done due to the standardisation of the kilometrage, it is possible to record results extending over a distance well in excess of 100 000 km which represents the maximum individual kilometrage, and this we have done.

At present, about one half of the Diesel power units have had their first overhaul. All the units of each type can therefore be divided into two groups: the first group comprises those locomotives which have not yet undergone their overhaul, and which have covered about 450 000 km for type A, and 600 000 km for types B1 and B2. The second group comprises the motive power units which have already had their first overhaul, and have covered between 0 and 150 000 km since that time. This group consists exclusively of A and B2 type vehicles since none of the B1 type has been overhauled so far.

With Diesel units just overhauled, the determination of the typical concentration curve presents no problem since the age of the oil bath coincides with the total kilometrage, at least for the first 100 000 km. Cases of unscheduled oil changes are rare, and we have had not difficulties in dealing with them.

With vehicles which have covered 500 to 600 000 km, there is a discrepancy between the age of the oil bath and the total kilometrage, due to unscheduled oil changes and irregular pollution of the oil. Two engines with the same kilometrage may have oil baths of greatly different age. When plotting the corresponding points on the p.p.m./kilometrage chart, we found that they do not correspond with the picture envisaged in chapter 2 (fig. 4).

In order to obtain a coherent picture of the concentration curve, the age of the oil bath must be taken into account. Seeing that the life of an oil bath may vary, as between one engine and another, between 100 and 200 %, we have adopted a standard kilometrage of 150 000 km for types A and B2, and the obligatory kilometrage of 50 000 km for type B1.

For all engines A and B2 with a total kilometrage below 150 000 km, the representative point of concentration has been plotted in the first section of 150 000 km where the abscissa coin-

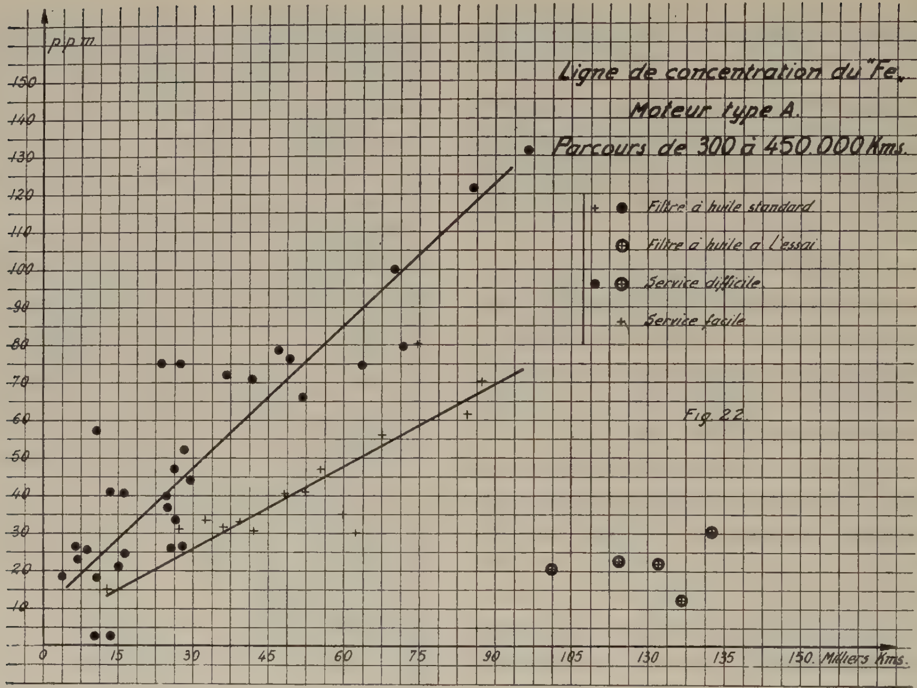

Fig. 22. — Concentration line for iron, engine type A, having covered between 300 and 450 000 km.

Explanations of the French terms :

Milliers kilomètres = thousands of kilometres. — Filtre a huile standard = standard type oil filter. — Service difficile = heavy duty. — Service facile = light duty.

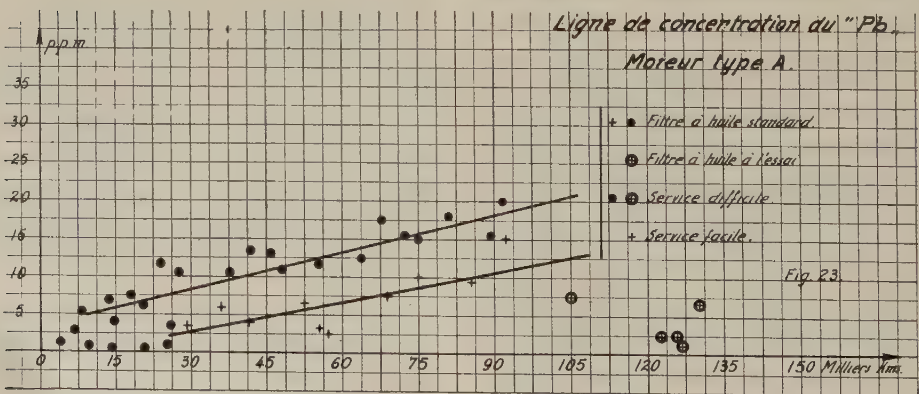

Fig. 23. — Concentration line for lead. (Legends as for fig. 22.)

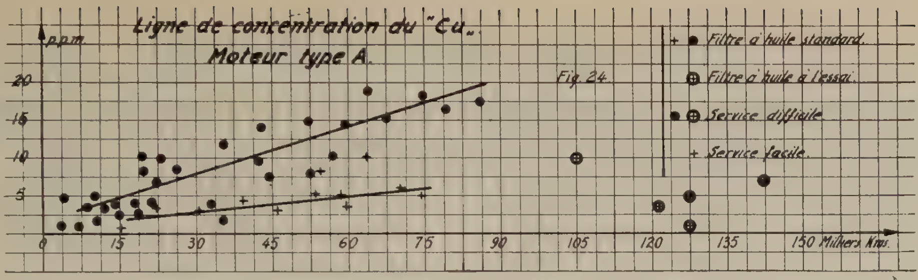

Fig. 24. — Concentration line for copper. (Legends as for fig. 22.)

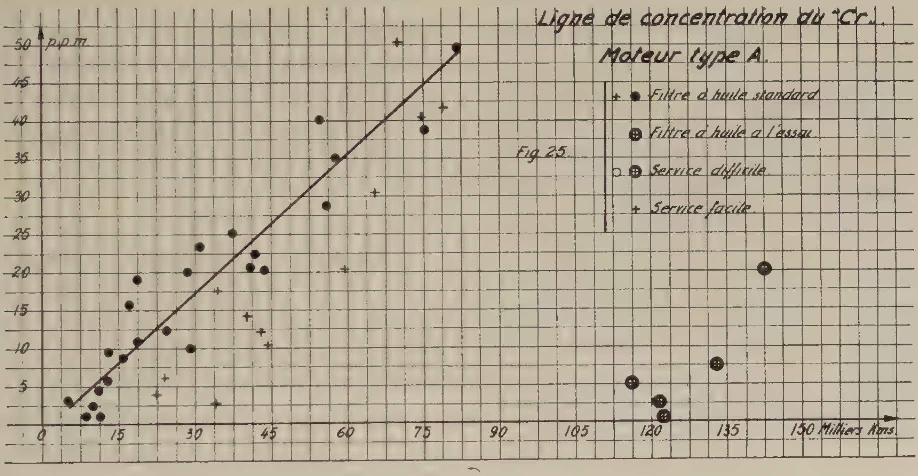

Fig. 25. — Concentration line for chromium. (Legends as for fig. 22.)

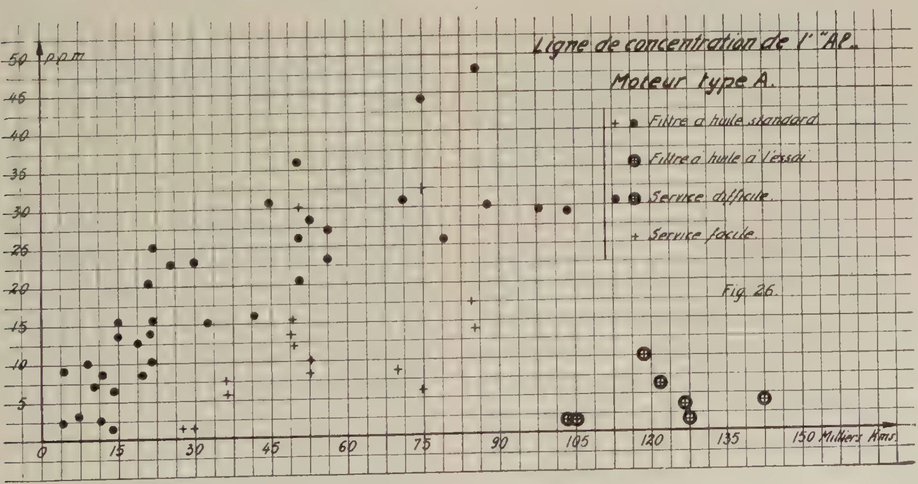

Fig. 26. — Concentration line for aluminium. (Legends as for fig. 22.)

cides with the age of the oil bath. With an engine which has covered, say, 230 000 km and where the oil bath has a kilometrage of 60 000 km, the point will be plotted in the second section of the total kilometrage, i.e. between 150 000 and 300 000 km, at the abscissa 60 000 km. This approximative method is the only one open to us at present, in view of the short experience at our disposal.

Figures 22, 23, 24, 25 and 26 show, for type A vehicles, the concentration lines of iron, lead, copper chromium and aluminium, respectively, for the first section of the total kilometrage, i.e. between 0 and 150 000 km. As the total kilometrage covered by the power units increases, we shall be able to plot further points and to complete the charts.

Each of these charts shows three series of points which are marked by a circle, a cross and a ringed cross, respectively. The significance of these symbols is explained below.

5.3. *Control of filter quality.*

5.3.1. *Effectiveness of the filters.*

As will be gathered from figure 22, the iron content of the oil of vehicles of type A increases rapidly with the age of the oil. These engines, however, show a normal performance. For experimental purposes, two motive power units have been equipped with an oil filter of a new type. The results of the spectrographic analysis of one of these units have been marked on the charts by a ringed cross. This vehicle is allocated to the same shed as the others where the results of the analyses are marked by a circle. As the concentration of metallic elements was found to be much lower in the case of the vehicles equipped with the new filter, we must draw the conclusion that this filter is much more effective than the one used for the bulk of the series.

As a result of these tests, it has been decided to use the new oil filters for the whole series. The spectrographic analysis has enabled us to compare, under service conditions, the effectiveness of the two filters and has confirmed our impressions of the respective quality of the two types of filter units.

5.3.2. *Lack of filtration.*

With certain vehicles of an out-dated type, the filtration effect, for air as well as lubricating oil and fuel oil, is non-existant or very inadequate. We have been able to bring out this fact by comparing the iron concentration of the oil of these vehicles with that of vehicles equipped with good filters. The former amounts to between 800 and 1 000 % of the latter : one encounters normal concentrations for 200 to 250 p.p.m., compared with 20 to 30 p.p.m.

As we shall have occasion to show, later on, an excessive concentration of impurities is detrimental to the engine and leads to premature wear. By way of trial, the filtration system on some of these motive power units will be modified. The spectrographic analysis will enable us to quantity the effectiveness of the new filters and to compare different types of filters with each other.

5.3.3. *Influence of the type of duty.*

On charts 22 to 26, we have marked by crosses the metal concentrations for

Spectrographic analyses P.P.M.							
1 000 km	*Fe.*	*Pb.*	*Si.*	*Al.*	*Cr.*	*Cu.*	*Dates*
95	30	30	30	5	0	72	5-8-58
95	30	35	33	3	0	65	6-8-58
96	43	48	30	2	0	175	9-8-58
97	43	45	30	4	0	165	11-8-58
97	53	49	30	0	0	260	12-8-58
0	7	0	0	6	0	3	14-8-58
1	8	1	0	3	2	4	16-8-58
2	8	20	17	7	20	16	20-8-58
3	12	3	13	4	0	5	22-8-58
4	8	2	3	5	2	6	25-8-58
10	11	2	1	3	0	10	3-9-58

Fig. 27. — Service life of the oil bath.

those type A vehicles which perform a less strenuous duty than the other vehicles of the same type. For this purpose, the specific fuel oil consumption, in kilograms per kilometre, has been used as a criterion.

The units included in the light duty category have a specific fuel consumption which is 20 % below that of the other units of the same type. For the same kilometrage, their engine wear should therefore be less. This is confirmed by the fact that the metal content of the lubricating oil is lower.

5.5. *Service life of the oil bath.*

It has already been stressed repeatedly that, if the concentration of impurities exceeds a certain value, the impurities act as abrasives and accelerate the wear of the engine. It would therefore be preferable to limit the service life of the oil bath even if the conventional physico-chemical analyses do not reveal any anomalies.

To support our thesis, we shall follow the spectrographic progress of the oil bath of a given locomotive.

During the overhaul, this locomotive was equipped with a new engine taken from stock. When the spectrographic analysis began to be applied, the locomotive, and its oil, had covered 95 000 km. This was, incidentally, the only overhauled locomotive equipped with a new engine. The results of

Fig. 28. — Photograph of damaged piston No. 6.

the successive analyses are shown in figure 27.

When the kilometrage approached 97 000, the concentration of the different elements was found to increase considerably.

Near 98 000 km, the concentrations became clearly abnormal, and these results were confirmed by successive analyses carried out every two days.

In view of the otherwise satisfactory results experienced with this type of engine and our lack of experience in this matter, the big end bearings were inspected, and everything appeared normal. An oil change was ordered although the conventional physico-chemical tests had shown normal results. A short while after the oil change, the concentrations of the different elements decreased. The oil filter was effective, and at present, the metal contents have decreased to the levels normal for the age of the new oil bath.

The only possible interpretation of these results can be that wear had been caused by the impurities in the oil. If the abnormal content of impurities had

Fig. 29. — Another photograph of damaged piston No. 6.

been caused by the poor performance of any particular part of the engine, it would not have been possible to improve the working of the defective part merely by changing the oil, especially as the physico-chemical tests of the oil bath had yielded normal results.

Moreover, we have also been able to ascertain that the prolonged retention of the oil in railcar engines leads to a rapid increase in metallic impurities at the end of the service life of the oil.

It is still too early for us to settle this question, but we think that the problem of the service life of the oil as a function of its content in metallic impurities must be tackled. We shall carry out research in this field by varying the service life of the oil in motive power units working under identical conditions.

If these first findings are confirmed, the service life of the oil would be not merely a function of the conventional physical and chemical characteristics but also of the concentration of metallic impurities suspended in the oil, and the results of the spectrographic analysis of the oil would have to be taken into consideration, especially on motive power units where the filtration is inadequate.

5.6. *Prevention of damage.*

The detection of damage is based on a comparison of the typical concentration lines and the variation in the concentration of the elements concerned for the engine in question. Up to now, we have not yet been able to determine these lines for all the motive power units.

In order to determine the limit between normal and excessive concentrations, we have proceeded with the examination of engines where the test results appear to be clearly suspect. This has enabled us to detect a number of cases of damage. By way of example, we shall discuss three particularly typical cases.

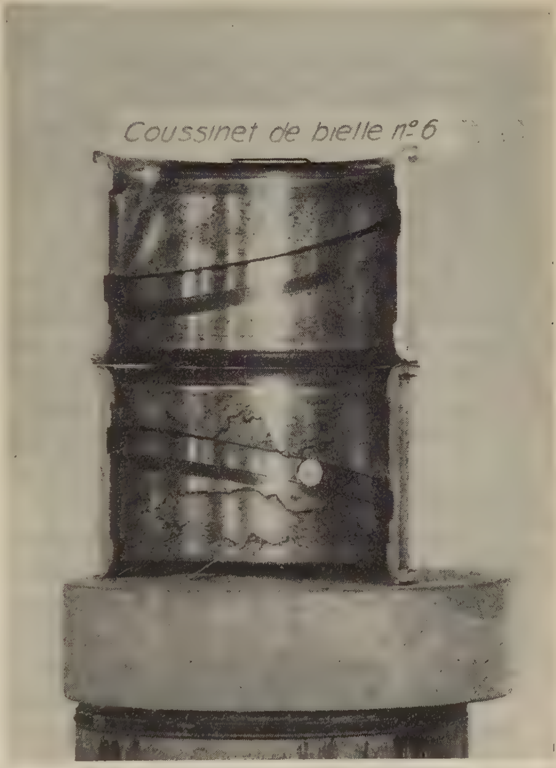

Fig. 30. — Photograph of damaged big-end bearing No. 6.

One railcar engine was subjected to spectrographic control for the first time. It was known that both air and oil filtrations were inadequate on this type of stock.

The following results were obtained :

Fe	*Pb*	*Si*	*Al*	*Cu*	*Date*
200	26	10	73	70	le 6.8
206	40	27	65	94	le 21.8
240	65	10	120	115	le 15.9
55	16	4	41	26	le 19.9 after oil change.

This sequence of the results seemed alarming to us, especially as regards copper and aluminium. It was arranged for the engine to be withdrawn from service and to be dismantled at the central workshop for examination.

It was found that the circlip of the axis of piston No. 6 was broken and had caused deep scratches in the cylinder and changes to the piston. Moreover, the leadbronze big end bearing of rod No. 6 was greatly affected by fatigue. The damage suffered by piston and bearing can be seen in the photographs (figs. 28, 29 and 30).

The case is typical since no external inspection of the engine would have given rise to the suspicion that the circlip was broken. In this case, the spectrographic analysis had played its part to perfection and had effectively « auscultated » the engine.

Another outstanding case.

The results from another type of railcar showed the following sequence :

Fe	*Pb*	*Si*	*Al*	*Sn*	*Cr*	*Cu*
120	55	45	20	4	5	0
160	65	75	70	6	4	1
210	68	90	110	45	5	210

Although the kilometrage attained was only half that normal for this type of engine, it was decided to send the engine to the central workshop for examination. The laboratory advised that the bearings should be inspected and the wear of pistons and cylinders ascertained.

After dismantling, it was found that the wear of the bearings, cylinders and pistons had reached four times the value normally encountered towards the end of the overhaul interval. Some of the bearings had greatly deteriorated through wear, though no major local damage or fracture was found. In view of the condition of the engine, it was however thought necessary to proceed with the overhaul at once.

A third case.

The engine of a shunting locomotive showed the following results :

Fe	*Pb*	*Al*	*Cu*	*Date*
200	230	32	270	26. 9.58 oil change and repair
74	42	~5	54	1.10.58 after oil change
104	8	12	36	10.10.58 (after 1 000 km)

Because of the absolutely abnormal concentration of copper and lead, the engine was taken out of commission on 27th September. On dismantling, it was found that several bearings fouled the bronze. After replacement of the bearings and oil change, the concentrations decreased as shown by the analysis of samples taken on 1st and 10th October.

The absence of effective air and oil filters is reflected in the very rapid increase in iron concentration.

5.7. *Water infiltration.*

First case.

The engine of a main line locomotive showed the following results :

Fe	*Pb*	*Si*	*Al*	*Cr*	*Cu*	*Date*
47	8	22	5	39	2	28.8
46	4	22	19	93	5	5.9
37	8	18	29	152	6	12.9
40	17	48	30	168	13	21.9

This engine was equipped with chromium-plated liners and at the time concerned, the cooling water of the Diesel engine was treated with chromate. Meanwhile, the borate treatment has been generally adopted.

In this case, the wear of the liners was certainly not the cause of the excessive chromium concentration since the iron concentration had remained unchanged, and any wear of the liners must be accompanied by an increase in the iron concentration.

The chromium increase could only be due to water leakage. On 23rd September, the maintenance department at the depot was asked to investigate the cause of the water infiltration. It was found that the cross-pieces of several cylinder heads had to be repaired.

Second case.

From a railcar engine, the following test results were obtained :

Fe	*Pb*	*Si*	*Al*	*Cr*	*Cu*	*Date*
150	25	31	84	40	118	3.9
150	40	60	100	64	120	8.9
150	40	75	110	80	105	10.9

The increase in chromium concentration was very rapid. The depot was asked to check for any water leakages. It was found that one cylinder head was broken.

The problem of water infiltration is of prime importance since water rapidly attacks the bearings and gives rise to major wear.

The spectrographic analysis is the most sensitive means of detecting water infiltration. If water leakages were to be detected by chromatographic methods, the water would have to be present in the oil when the sample is taken. More often than not, however, the water will already have evaporated and will have combined with the combustion products to produce acids which attack the bearings.

But chromium or boron remain in the oil and leave a visible trace of the water infiltration.

In this way, the spectrographic analysis is of considerable importance in tracing water leakages.

6. **Conclusions.**

We have, one by one, examined the general principles which have guided us in the application of the method of spectrographic analysis to the control of lubricating oils of Diesel engines. By quoting some noteworthy examples encountered during the first six months of the operation of the spectrograph, we have shown that the spectrographic method is able to render irreplaceable services for :

1) testing the filtration, air and oil of the engine assemblies and comparing different filter systems with each other;

2) detecting water leakages, even very slight ones, in order to obviate the deterioration of bearings;

3) measuring the influence of heavy and light duties on engine wear;

4) studying the influence on engine wear of the concentration of metallic elements suspended in the oil, with a view to limiting the service life of the oil if the influence of abrasive wear can be proved;

5) detecting abnormal wear and incipient damage by the examination of concentrations which are abnormal and excessive compared with the typical concentration lines.

To be carried out successfully, this programme will require several years of study and research. The fundamental condition for the success of the programme is to concentrate, in the same hands, the analysis itself, the interpretation of the results, and the inspection and check-up of the engine.

For that reason, the choice has fallen on a direct-reading equipment which has the following dual advantage :

1) due to the automatic working of the equipment, the time required to carry out an analysis is less than three minutes, including the conversion of the readings by means of the measuring bridge into degrees of concentration. In consequence, the head of the laboratory can spend most of his time on the interpretation of the results and the inspection and control of the engines;

2) by reducing the number of manipulations to a minimum, the risk of errors is reduced, and the repeatability of the results attains a very satisfactory level, as the relative root mean square deviation varies between 5 and 9 %.

To make it easier for the head of the laboratory to inspect the engines, the laboratory has been installed in an annex of the workshop charged with the overhaul and major repairs of Diesel electric locomotives. In this way, the head of the laboratory can easily keep a check with his diagnosis and can see to it that the spectrographic analysis does not remain a theoretical exercise without any influence on the life of the engine assemblies.

If we dwell on this aspect of the matter, this is because we all know from experience that the modern research methods emerging from the research and development laboratory into industrial life always meet with the same difficulty : an apparatus excellently suited to describe and explain theoretical phenomena is incapable of dealing with the many aspects of a mechanism which works and wears out.

To render any technique based on the use of scientific instruments really effective, it is necessary to bridge the gap between the results obtained by the research method and the system subjected to the control.

The results furnished by the control apparatus represent a code which is useless as such. It only becomes useful in the light of a method of interpretation which translates the figures supplied by the apparatus into the language of the mechanical engineer.

In our case, the problem of interpretation consists in providing, on the strength of the concentration of metallic elements suspended in the oil, a picture of the

mechanical performance of the Diesel engine and certain accessories.

A precise diagnostic of the engine is not feasible because of the many factors, including some outside our control, which have an influence on the condition of the engine.

What we do, however, expect from the spectrographic analysis is to reveal a trend and to alert us if there is a risk of the proper working of the engine being jeopardized by abnormal phenomena.

We are aware of the fact that only a prolonged experience based on a thorough knowledge of the engines, and especially their weaknesses, will permit the establishment of interpretation criteria of high validity.

Our objective will have been accomplished if we have succeeded in describing not only the apparatus and methods used for the analysis but also the general policy and programme which we intend to follow in carrying out the spectrographic analysis of the lubricating oils of Diesel engines.

We do not wish to conclude this article on the spectrography of lubricating oils of Diesel engines without mentioning Mr. Barth, Chief Engineer, Chicago and North Western Railway System, Chicago, Ill. Due to his enlightened advice and his great experience in the subject, he has no doubt enabled us to avoid quite a number of mistakes. We have to thank him for the kindness with which he has made his competent knowledge available to us.

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by Dr.-Eng. G.A. Gaebler, Frankfurt-on-Main.

(*Eisenbahntechnische Rundschau*, No. 2 and 3, February and March 1958.)

PRELIMINARY REMARKS.

When some eight years ago, the Deutsche Bundesbahn had the opportunity to study some new Diesel engines, they found themselves faced with a serious decision regarding the choice of the transmission system. All technical progress had been interrupted for nearly ten years by the war and its sequels. There was a very definite break in the parallel perfecting of electric and hydraulic drives which had been started just before the beginning of the war, and had given first results of great interest. During the war and immediately afterwards, a great number of Diesel engines with electric transmissions were built in other countries, in particular in the United States. Experience in operating with electric types was therefore very extensive; in the case of the hydraulic types, on the other hand, apart from a few small transmissions, experience was only based in the case of average and high powers on a few prototypes mostly built in Germany and only tried out in practice with very few examples.

However, the D. B., after a considered examination of the technical level of the evolution, and in particular its experiences concerning hydraulic and electric transmissions, decided to begin by taking the hydraulic drive as the basis of all future studies of Diesel units, from the low powers up to the highest, for both long distance railcars and heavy Diesel locomotives, because they were convinced that this type of transmission, still in its infancy, had definite advantages and possibilities of improvement far exceeding anything already known in actual installations, and consequently only verifiable in practice.

The time has now come to sketch in broad outlines the work of improvement carried out during these eight years and the results obtained during trials, taking as basis in part the several types and applications of a certain power, and bringing out at the same time to what extent the path followed has proved to be correct in the light of the knowledge acquired in the meantime. Experience to date has already proved sufficient to lead the German Federal Railway to order and put into service a large number of powerful series units with hydraulic transmission to provide a practical confirmation of this provisional decision.

We have purposely and with the greatest frankness quoted examples in the following article of technical incidents occurring at the time the designs were being perfected and trials made in order to facilitate our explanations. These show that the perfecting of the components of engines of this type in order to make them absolutely suitable for the services they will have to assure involves an extremely thorough study of the design. It often happens in fact that very slight mistakes in design, which even an experienced builder may overlook, may be the source of definite trouble, which often does not appear until the engine has been working for a considerable period, and often only in service and not on the test bench. These incidents, which at first cause surprise, can be completely eliminated as soon as the cause is ascertained with a minimum of technical means.

Such troubles as experienced at the beginning of the working in service are quoted here as examples together with details of the constructional modifications which they led to; they cannot on any account be used as a basis from which to evaluate the type of transmission in question, a fact which must be stressed, obvious though it may be to any experienced engineer. Moreover, the errors or defects mentioned have all been eliminated subsequently, together with their repercussions, so completely that no further trouble has been experienced.

We will end these preliminary remarks by stating that after eight years the German Federal Railways are more convinced than ever that their choice of hydraulic transmissions for their power units was and is the right one. This conviction does not appear likely to be modified in the foreseeable future, even though as is obviously its duty the D. B. continues to follow the evolution and possibilities of improvement of other types of transmission, and may possibly take part in practical trials and tests thereof.

DEFINITION OF HYDRAULIC TRANSMISSIONS.

Amongst the hydraulic transmissions used for the transmission and conversion of the torque between the Diesel engine and the driving axles of the vehicles are included, interpreting the term in its widest meaning, all systems of transmission in which the torque of the engine is transmitted, over the whole speed range of the vehicle or part thereof, to the elements of the mechanical drive or of the live axle by means of a hydraulic component. From the point of view of the method of work and action, there is a fundamental difference between the hydraulic components having a characteristic of coupling, in other words a characteristic which does not show any notable variation in the torque on outlet and on entry (the hydraulic couplings) and those which, fitted with directing devices, make the torque vary as a function of the speeds of rotation of the primary and secondary (hydraulic torque converters). According to the method of using the couplings or converters and the type of combination with the mechanical drives fitted before or after them, a distinction can further be made between purely hydraulic transmissions and hydro-mechanical transmissions. The O.R.E. (Office for Research and Experiments) of the I.R.U. (U.I.C.) stated its views on this point as follows :

Hydraulic transmission.

Hydraulic transmissions include all types of transmission containing hydraulic elements, in which the whole of the power is transmitted over the whole range of speeds by one or several hydraulic components necessary for the functioning of the transmission.

Hydro-mechanical transmission.

Hydro-mechanical transmissions include all types of transmission embodying hydraulic elements, with which the power is not wholly transmitted over the whole range of speeds by one or several hydraulic elements necessary for the functioning of the transmission.

According to this definition, transmissions with torque converters only, for example, are hydraulic transmissions, whereas the « split drive or differential transmissions » (Leistungsteilergetriebe) constitute hydro-mechanical transmissions.

We will content ourselves with this brief report, which is necessary for the comprehension of what follows. We do not propose to describe the design and method of functioning of hydraulic transmissions. There is already a whole series of excellent articles by qualified authors on this subject. Nor do we propose to take sides in the still very active controversy regarding the advantages and drawbacks of the

classic types of electric transmission compared with the newer systems of hydraulic transmission. This subject has also given rise to some remarkable publications [1]. We will merely state :

Electric transmissions have given complete satisfaction for dozens of years on thousands of engines, especially at average and high powers. For this reason it is still favoured by many railway Administrations. It must not be forgotten in this connection that, perhaps because of the competition from the hydraulic transmission, it is constantly being improved in its different parts, so that today it is still possible to design transmissions with a good efficiency, lighter and cheaper than most of the old types.

The first beginnings of the *types of hydraulic transmission and drive* were made very difficult by the presence of this powerful competitor. They had to proceed very slowly, beginning with the lower powers and progressing up to the highest powers of Diesel engines now used in railway work. They did arrive in the end, thanks to their low weight, the ease with which they can be made, and their low cost price, their suitability to rough operating conditions as has been proved by the perfected, tested and finished types introduced since then, and the resulting relatively low maintenance costs.

In view of the way the two types have striven to *increase their efficiency*, it must be recognised that on both sides the progress made in recent years has been remarkable.

We will examine now the technical progress of the hydraulic transmission, from former times to to-day, by means of various examples, in the light of the experience gained in actual operation by a large railway Administration which, as we said above, had decided after thorough consideration and a study of the problem as a whole, to apply this principle on a wide scale on its Diesel vehicles now on order or on the drawing board. We will take the opportunity of stressing at the same time those points to which special attention should be given both from the technical and operating points of view, if completely satisfactory long term results are to be obtained.

THE EVOLUTION OF HYDRAULIC TRANSMISSIONS FOR DIESEL ENGINES.

The idea of transmitting power by means of liquids is not a new one. An old print, for example, shows water being raised by means of a gear driven by a horse in a round-about into a tank from which it flows onto a paddle wheel, similar to a Pelton wheel, in order to turn the grinding wheel. This shows that our ancestors often thought along the same lines as we do. The only difference is that the means at their disposal were much more primitive, so much so that the results of reflections of this kind were often disappointing. When at the beginning of this century, *Föttinger* proposed, after inventing his pump for liquids, to feed the fluid raised by the pump directly into a turbine in order to set in motion slowly and with great force the shaft driven by the turbine, even though there was a considerable difference in the speed of rotation of this latter and that of the pump, the railways showed very little interest in these proposals, although *Föttinger* had already adopted the fixed guiding device in the installation he had designed and had thus created a veritable torque converter. The railways at that time only used as prime mover, apart from a tentative appearance of electric motors, steam piston engines, which had a satisfactory torque at low speeds as well as at high speeds. It was

[1] Amongst these publications, we will only mention : Dr.-Ing. GÖSSL : « Dieselhydraulic und Dieselelektrik » (The Diesel-hydraulic and Diesel-electric systems). « E.T.R. », 1955, No. 10. KNOBLOCH : « Dieselhydraulik oder Dieselelektrik » (The Diesel-hydraulic or Diesel-electric systems). « Techn. Rundschau », Berne, 1955, No. 22 of the 20th May.

only when the internal combustion engine, in particular the Diesel engine, had achieved a state of technical development which made it suitable for use on railway vehicles, that the principle of the transmission and torque converter, which in the meantime had been perfected for other uses, increasingly attracted the attention of the designers. The internal combustion engine has the peculiarity that it must revolve at a certain minimum speed before it can transmit any torque to the driven shaft. Mechanical transmissions, used with success at low powers, could no longer be designed with friction clutches suitable for the construction of vehicles as the powers of the engines increased together with the starting torque and speed changes to be absorbed in the couplings. The proposals put forward, at an early stage, to make use of generators and electric motors for the conversion of the torque, were used first of all for the high powers favoured by the experience acquired in the construction of electric locomotives and railcars; it is true that the need to install the power three times over in separate elements was a drawback from the point of view of purchase price and operating costs.

Hydraulic torque converters and couplings were perfected principally in Germany. This explains why this method was studied at an early date, about as far back as 1930, by the Deutsche Reichsbahn, as regards the possibilities of making use of it, and was soon given a trial under practical operating conditions. Perhaps, it is not realised how many types of vehicles have been fitted with hydraulic drive since that period. According to the present series numbers, there were :

Fast railcars (up to 160 km/h) :

« Leipzig » (2 × 600 HP) and « Kruckenberg » (not used in normal service);

Railcars (up to 120 km/h) :

18^5 (2 × 410 HP), 19^5 (2 × 450 HP), 20^5 GVT (600 HP), 32^5 (420 HP), 36^5 (360 HP), 45^5 (2 × 275 HP), 46^5 (410 HP), 60^5 (225 HP), 73^5 (200 HP), 90^5 (2 × 200 HP panoramic railcar), 99^5 (180 HP);

Locotractors :

No. II power group (40 to 105 HP);

Diesel locomotives :

Series V 140 (1 400 HP trial prototype).

After a long gap, the German Railways, towards 1948, again had the opportunity to design some new vehicles in conjunction with the firms who formerly collaborated with them in this field. It was only logical to start from the pre-war designs and the experience acquired with the above mentioned vehicles during and since the war, without however coming to any final decision as regards the future choice of the transmission for the new motor units. At this epoch, thanks to the technical experience obtained in Germany with these transmissions, it was possible to design and build within a relatively short period greatly improved types with much better operating characteristics. This resulted in the first post-war prototypes, which made use of powerful hydraulic transmissions in conjunction with Diesel engines having a nominal output of 800 HP at the motor shaft at a speed of rotation of 1 400 r.p.m. The choice of such types was much discussed at the time because it was considered that such engines were particularly « fast », but apart from its other advantages, this high speed was favourable for hydraulic transmission, the design of which had to be adapted to high speeds of rotation. These transmissions, made by VOITH (Heidenheim) and MAYBACH (Friedrichshafen) were the first modern types, with VOITH transmissions for medium powers used before the war for shunting locomotives, for example the design with jack and rod drive.

Nor must we forget to mention the low power transmissions which gave the best results on the standard design Diesel locotractors, and finally the simple hydraulic couplings, such as those used, for example, on the first large series of ultra-light vehicles of the D. B. the « Railbus »,

because they gave an excellent efficiency reaching as high as 98 % and were very good at starting and for damping out vibrations.

These 800 HP engines with hydraulic transmissions with torque converters were used in the first place on the new types of railcars (VT 07, 08, 12) of the Deutsche Bundesbahn and on a trial series of four axled Diesel locomotives with bogies (V 80); as operating results were encouraging, they were also fitted to the big Diesel locomotive with two engines (V 200) which was designed with the same constructional components as the V 80. On all these vehicles, after exhaustive preliminary studies, the live axles were — experimentally to begin with — driven by the secondary shafts of the hydraulic transmission by means of *cardan shafts,* which was still a novelty, especially in the construction of locomotives, when we remember the torque to be transmitted, which is naturally much greater than on motor cars, where the motor power is considerably lower and the running conditions more favourable as the wheels are fitted with rubber tyres. As the transmission by cardan shafts and, also, the axle drive, which is generally mounted on the non-suspended axle, are important elements in the transmission as a whole of modern designs of motors, we will devote more space to the results these gave in service.

TRANSMISSIONS FOR DIESEL ENGINES ON THE POST-WAR RAILCARS OF THE GERMAN FEDERAL RAILWAY.

1. Light railcars (Railbuses).

On the light railcars (Schienenomnibus) with one or two engines (series VT 95[9] and 98[9]) of the D. B. a six speed mechanical transmission is used with an electromagnetic clutch made by the Zahnradfabrik Friedrichshafen (type 6 E 75 S) in conjunction with a hydraulic coupling for changing speed and starting. The *hydraulic* coupling which, on account of its characteristics, requires no manipulation, gives a smooth connection between the engine and gear box, which protects the gears during the operations of starting and changing gear achieved by means of the electromagnetic friction clutches, and has made it possible, by means of a very simple remote control, to drive several engines in a rake of small railcars. We will merely mention here this very simple application of a hydraulic system. In operating practice, it gave excellent results.

2. Locotractors.

On the standardised power group II locotractors of the D. B., on which the Diesel engine develops a power of about 120 HP, a VOITH hydraulic transmission with three speeds (type L 33 U) is used. This consists of a converter for starting and two speeds consisting of hydraulic couplings. The gear change is completely automatic, as *changing* from first to second and from second to third speed depends entirely *upon the running speed.* This transmission is also of a well tried type, which has been in use for a long time. Its qualities deserve to be stressed, especially when it is remembered that locomotives used for shunting which is a particularly hard type of service in railway operating, are driven by men having no previous technical training.

3. Long distance railcars.

In the VT 10[5] main line railcars (articulated sets), prototypes of which are in existence, an EMG (AEG) (type SL 250/W 360) four speed hydro-mechanical transmission is used. This takes from the Diesel engine an input power of 210 HP and works in the first three speeds by means of a constantly full torque converter; the gears are engaged by a disc friction clutch. At fourth speed, the engine is connected *directly and mechanically* to the output shaft by means of an identical friction clutch. The change of gear works

automatically. There is not yet sufficient experience of this transmission, of which a few specimens only have been made, for its results to be discussed.

4. Types V 60 and V 65 Diesel locomotives.

For the series V 60 shunting Diesel locomotives, 270 units of which are now being delivered, as well as for the prototypes of the Series V 65 for secondary lines, a VOITH three speed hydraulic transmission has been adopted (type L 37 zUb) the maximum input power of which is 800 HP. Like that of the locotractors, this transmission includes a torque converter for starting and two hydraulic couplings, but the completely automatic control works by the *regulation of the secondary and primary* as a function of the running speed, on the one hand, and of the fuel supply to the engine on the other. This transmission is derived from the type L 37, a great number of which have already been used on the D. B., on the old V 36 locomotives of the Wehrmacht, on private railways, and on types for other countries. Its history shows that it is one of the oldest. which has stood the test of time, and it has given satisfaction on the prototype locomotives, as well as on the series engines, since delivered, of the V 60 type, as well as on the experimental type V 65 engines.

5. High power Diesel locomotives and multiple unit sets.

On the big locomotives of series V 80 (experimental type) and V 200 (experimental and series types) as well as on the multiple unit sets of the series 07, 08 (main line sets) Vt 11 (TEE sets) and VT 12 (interurban services), for the same purpose, use has been made of :

a) *the VOITH three-speed hydraulic transmission;*

b) *the MAYBACH four-speed hydraulic transmission,* working with a clutch controlled converter followed by four mechanical speeds.

At the present time, these are the most powerful types of hydraulic transmissions built in Germany since the war, and they have been in service about long enough on the locomotives and railcars for the results got to be judged.

Both are purely *converter types.* It should not be concluded that preference should always be given to this type of transmission in designing modern vehicles and transmissions; on the contrary, in addition to the type L 37 zUb VOITH transmission of average power used on the new V 60 shunting locomotive, higher powered units are also being studied, in which the engine is connected to the driving wheels by means of hydraulic couplings, especially in the high speed range.

Formerly, a whole series of objections was raised against using *hydraulic couplings for changing gear.* The first argument was the *reduction in the speed of rotation* when running slowly, which is undesirable for the working of the engine under high loads, and the *limitation of the use of the power* of the Diesel due to this reduction in the speed of rotation. This drawback is undeniable. However it is possible to minimise its effects by limiting the scale of speeds of the couplings to working under full load by a careful calculation of the demultiplication ratios of the mechanical gear train and the clutch as a function of the running speed and of the torque.

Another argument put forward is that at high running speeds and under part load, the Diesel engine *always has to turn at a high speed of rotation* and consequently is subjected to considerable wear. This objection is also justified, although present day Diesel engines are not as sensitive as the old ones were in this respect. But there is no lack of suggestion aimed at limiting automatically running at low power at high speeds, and to drive at these rates, either at high running notches, or free wheeling by cutting off the power.

Naturally, this drawback of changing speed by couplings at part loads of the Diesel engine generally involves an *increase*

in the specific fuel consumption. But with careful design of the characteristics of the engine and the transmission, the *savings* obtained by the *higher efficiency of the couplings,* compared with torque converters, will always exceed what is lost through the somewhat greater specific consumption of the engines, especially at high powers. The *savings in fuel* obtainable by using hydraulic couplings are shown in the graph of figure 1 for an example calculated on the basis of existing engine and transmission factors. At high running speeds, they vary between 1 and over 10 % according to the power transmitted; in practice, such savings have an appreciable effect upon the overall fuel consumption.

Finally, mention is made of the drawback that the *hydraulic coupling* gives a practically rigid mechanical connection between the engine shaft and the axle. If anything goes wrong with the mechanism, it will still be driven by the axle, which may lead to damage. In the present state of the technique of designing transmissions, it is however possible to provide constructional devices which will automatically remedy this state of affairs, for example by emptying the coupling.

EXPERIENCE OF THE D. B. WITH 1 000 HP TRANSMISSIONS.

In the 1 000 HP category of powers, at the present time, use is made of :

a) VOITH T 36 or LT 306 r transmissions;

b) MAYBACH K 104 or K 104 US/SU transmissions.

These two types are interchangeable at will, without any modification to the vehicle, its engine installation or drive, and they can be used at will on the type VT 07, 08, 11 and 12 railcars and V 80 and V 200 locomotives.

The four types of transmission only differ essentially in the possible arrangement of the output shaft flanges : the T 36 and K 104 types with lateral drive can only be fitted on the railcars and V 80 Diesel locomotives; the types LT 306 r and K 104 US/SU with the secondary drive arranged either at the side or below can be used on all vehicles.

1. T 36 and LT 306 r Voith transmissions.

The VOITH transmission consists of three hydraulic converters followed by mechanical gear trains with the gears always in mesh. The completely automatic drive, which is governed by the speed of rotation of the primary and secondary, is engaged by the emptying of the circuits of the converter which are not in use. This transmission comes within the highest

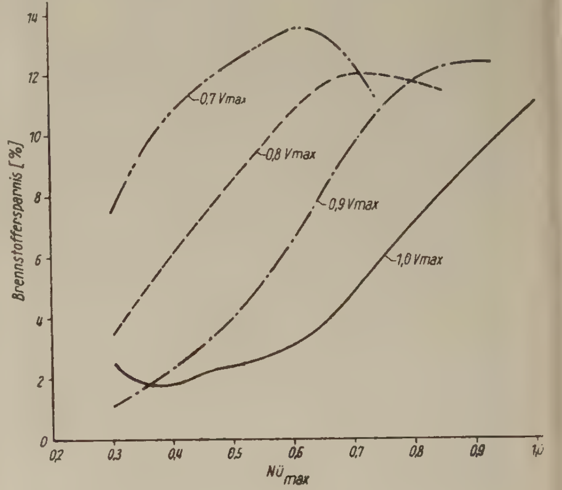

Fig. 1. — Fuel economy calculated as a function of the power absorbed and running speed of a Diesel locomotive with Maybach GTO 6 engine and Voith three speed transmission with hydraulic coupling in place of the torque converter at third speed.

N. B. — $Nü_{max}$ = maximum power transmitted. — Brennstoffersparnis = fuel economy. — Vmax = top speed.

power category of the D. B. at the present time, and has been improved in certain details or simplified in the last few years, on the basis of the experience acquired in operating or in the shops.

For reasons of standardisation, the German Federal Railway at first required this transmission to control changes of direction with a neutral position whilst the engine was stopped. This was subsequently given up. The present reversing gear, which is always placed in a position corresponding to one of the directions of running, makes it possible, thanks to the principle of engaging and disengaging by filling and emptying of circuits used on the VOITH transmission to control in a positive fashion all the engine installations of a set at any given running speed. In addition, the change of speed, which originally was electropneumatic-hydraulic, has been altered into an electro-hydraulic system, and consequently improved and simplified.

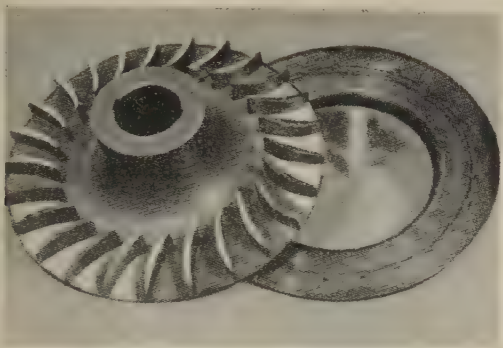

Fig. 2. — Turbine runner of the first Voith T 36 transmission with rivetted blades.

In its initial form, the transmission was built for a power at the input shaft of 800 HP, which then corresponded to the powers of the three types of 12 cylinder Diesel engines of 800 HP used for all purposes on the D. B. The input power was soon raised as a first stage to 1 000 HP, so that certain constructional details had to be adapted to the increased stresses. In the case of the first T 36 transmissions, the blades of the turbine runner were, contrary to pre-war practice which was to fabricate cast turbine runners, fixed to each other by rivets (fig. 2). With the stresses due to the high frequency pulsations in the liquid, this type of fastening was not sufficiently secure. The solution found, which also offered the possibilities of a further increase in power, was to mill the blades and ring from a blank, so that each turbine ring carries half the blades. The turbine rings formed in this way (fig. 3) are rivetted together. This arrangement, which is also advantageous as far as manufacture is concerned because the gaps between the blades are greater, has since proved its worth.

Originally, the *pump-impellers* were made of bronze. To avoid the tiresome repercussions of the poor resistance of this material to heat in the case of accidental metallic contact at high speed, the pump-impellers have subsequently been made of malleable cast iron, and finally of cast steel. The change in the material used was also advantageous for *fastening them to the shaft.* The original fastening by key and keyway no longer was satisfactory as the stresses increased. The present practice of using a hydraulic press to force the cast steel wheels on

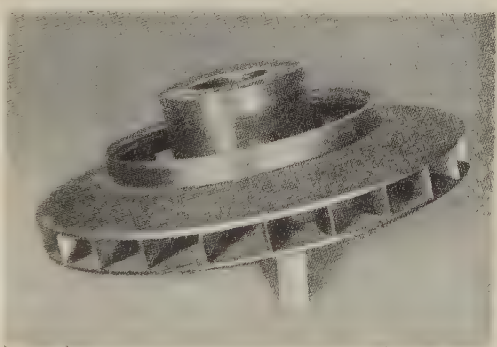

Fig. 3. — New type turbine wheel of Voith T 36 transmission, formed of two rings rivetted together.

the shaft is much better and gives to the whole the necessary resistance to possible torsion stresses.

The importance of a thorough constructional study, even in the case of simple accessories, is shown by the frequent breakdowns which occurred at the beginning owing to *damage to the oil pipes under pressure.* The thin piping, held in place by welded supports, which would have been quite adequate to support the uniform pressure of centrifugal pumps, gave rise to difficulties when geared pumps which set up pressure oscillations were used. The difficulty was at first met by putting the piping that gave rise to trouble outside and replacing the tubes by flexible hose. This solution was satisfactory from the

Fig. 4. — Toothed wheels; old and new patterns.

working point of view, but not from the constructional point of view. As a further improvement, it was subsequently replaced by another method of assembly, in which the pipes, which had thicker walls, were fixed by means of fastenings riveted at close intervals without causing stresses in the piping. In all the most recent transmissions, the piping is cast integrally in the gearbox.

In the beginning, difficulties also occurred on the *spur gear rims bolted on the flange of the shaft* in the multiplication gearing (fig. 4 to the left). According to the calculations, the fixing of the spur gear rims on the shaft was perfectly adequate, but the supplementary stresses due to rotational oscillations resulted in breakages of the fitted fastening bolts. This difficulty was overcome by considerably strengthening the bolts. At the present time solid spur gears are used (fig. 4, on the right).

We have already mentioned above that at the beginning the *transmission control* was pneumo-hydraulic; it has been altered and the pneumatic part eliminated, which has simplified and improved its safe work-

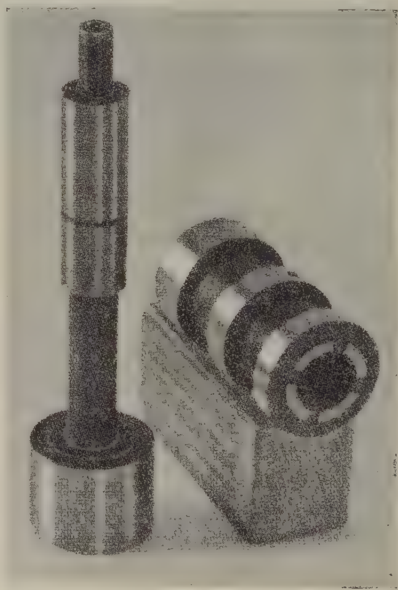

Fig. 5. — Piston of preselector in the hydraulic part of the drive of the T 36 transmission. *On the left,* distributor piston; *on the right,* on the wooden block, the floating piston.

ing; the compressed air switch valve of the original drive occasionally showed traces of rust, due to the humidity of the compressed air used, which can never be completely avoided. As a result, the valve was liable to get out of order. Today, according to a logical system for a hydraulic

transmission, which has proved its worth in the meantime, only oil under pressure is used for the control.

The stresses in the gear wheels of the two transmission *measuring pumps* were greater than was expected. These pumps supply the oil pressure needed for the drive and for operating the primary and the secondary. As a result of the wear on the gear faces, the amount of oil pumped fell off excessively, without this being noticed at first. The result was failures of the switch. A very slight widening of the gear wheels and the use of a harder material effectively remedied this defect.

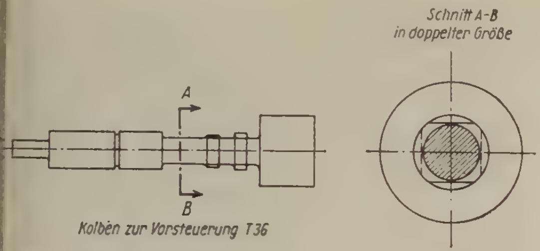

Fig. 6. — Distributor piston of figure 5, as now fitted.

N. B. — On the left : Piston for the preselector of the T 36 transmission. — On the right : Section A-B, double size.

The example of the *distributor pistons of the pre-selector* in the hydraulic part of the transmission drive showed what repercussions slight defects in the design can have. In the first example (fig. 5), the floating piston of the distributor was insufficiently guided in the gap between the large and small pistons, and sometimes got blocked. This drawback was remedied by fitting two guiding collars between the large and small pistons of the distributor, as shown in figure 6.

Another equally important modification was that made to the mounting of the *loose gears in the reverse gear* of the transmissions. As figure 7 shows, the reverse gear was originally assembled and arranged in such a way that the loose gear mounted on the shaft of the reverser had the same speed of rotation as this shaft, the side coupled to the sleeve of the clutch necessarily having the same speed of rotation as the former. The roller bearings therefore had no relative movement of their interior race compared with the outer race on one side or the other. As a result indentation appeared on the running surfaces of the races (fig. 8). In the new solution, shown in figure 9, the loose gears are no longer mounted on the shaft of the reverser, but in the gearbox of the transmission; this source of trouble has thus been completely eliminated.

To save weight, the big *transmission gearboxes* were first of all made of light

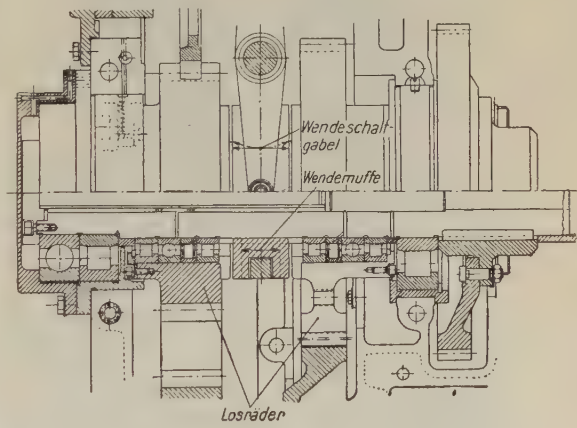

Fig. 7. — Clutch of the reverse gear of the Voith T 36 transmission. The loose gears are mounted on the shaft of the reverse gear. When the reverse gear is operated, one loose gear is in each position coupled to the shaft of the reverse gear by means of its sleeve; it then has the same speed of rotation as this shaft. On the other hand, the relative speed of the loose gear and the shaft is zero, so that the roller bearings no longer turn; hence the risk of the formation of indentations on the races.

N. B. — Wendeschaltgabel = fork of reverse gear. — Wendemuffe = sleeve of reverse gear. — Losräder = loose gears.

alloys (Silumin). But when these transmissions had to be repaired, occasionally — no doubt on account of the constantly variable heat stresses to which the gearboxes are subjected — difficulties were experienced in the alignment of the bearing seats. To increase the rigidity of the gearboxes, it was decided in the case

Fig. 8. — Stop marks on the rolling surfaces of the roller bearings of the reverse gear clutch.

of the type LT 306 r transmissions to go back to grey cast iron; the new gearboxes have given no trouble so far.

Finally, operating experience has also led to an improvement to the switch. The *emergency control* of the first transmissions, which made it possible, *in case of electric remote control breakdowns,* to get into the first speed manually, proved unsatisfactory in service, because the maximum speed of 40 km/h which could be reached in this way was too low. The possibility of working the controls directly by hand provided by the new arrangement makes it possible to work the transmission at the three speeds by direct manual operation. This arrangement of the emergency control has been much appreciated in practice in the few rare cases in which it has had to be used.

2. Maybach type K 104 and K 104 US/SU transmissions.

The Maybach transmission consists of a constantly full torque converter, followed by a four-speed mechanical gearbox with automatic control from the input and output sides of the transmission. Engaging the gears is done in a fraction of a second by means of a hydraulic control acting on the over-riding claw-clutch (locking claw-clutch), the converter being initially briefly disconnected with a break-

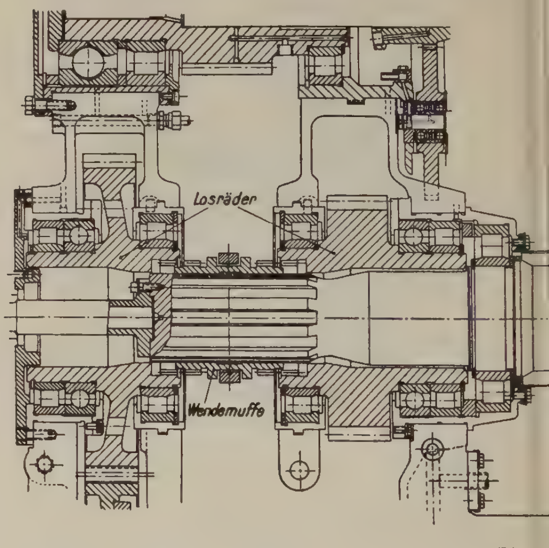

Fig. 9. — Clutch of the reverse gear of the Voith LT 306 r. transmission. Owing to the fitting of the loose gears in the gearbox, there is a relative movement in all the bearings at all positions of the reverse gear clutch, which eliminates the defect inherent in the T 36 transmission of all the bearings turning at the same speed.

N. B. — Wendemuffle = sleeve of reverse gear. Losräder = loose gears.

ing effect: in this way the change from one speed to another, although noisy, causes no radial stresses by the shock and thrust of the claw-clutches. In this way the mechanical engagement of such considerable powers under satisfactory conditions in service has been achieved technically. When this was being improved, provision was

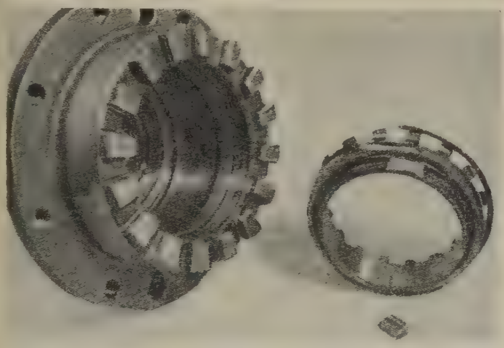

Fig. 10. — Broken multipiece locking dog-clutch.

made for the emptying of the torque converter at certain speeds; this helps to reduce fuel consumption when running idle and completely isolates the engines from the track.

The use of a *locking claw-clutch* reduces axial displacements of the claw rings and prevents the phenomenon of inversion in the immediate neighbourhood of the point of the claws. Since it was adopted, no further difficulties have been experienced with the gears. It is astonishing how quickly and safely changes of gear are carried out with this technique, which is not an easy matter with these large transmissions with their great mass forces, and considering the acceleration and deceleration of the rotation. It is true that the perfecting of the locking claw-clutch did not take place without a certain number of incidents having to be remedied. The lock-ring, originally in several parts, was not capable of standing up to the stresses to which it was subjected. Breaks sometimes occurred (fig. 10). After the rings were improved and the present monoblock type adopted (fig. 11) satisfactory reliability was obtained. All the new Mekydro transmissions are fitted with these locking claw-clutches for changing gears. Owing to the good results obtained, they have also been applied to the reverse gear; as a result, the gear change of a power installation at a given speed of running is also assured with this type of transmission; it has been adopted since series construction was started.

During these improvements to the design of the claw-clutch, based on the experience acquired in service, the *number of claws,* originally limited to 10, was increased to 16, which reduces the angular acceleration corresponding to a division.

A frequent trouble when these transmissions were first put into service, which was very troublesome because it led to the complete locking of the clutch-sleeve of the reverse gear upon its shaft, was the *welding of the clutch sleeve of the reverser*

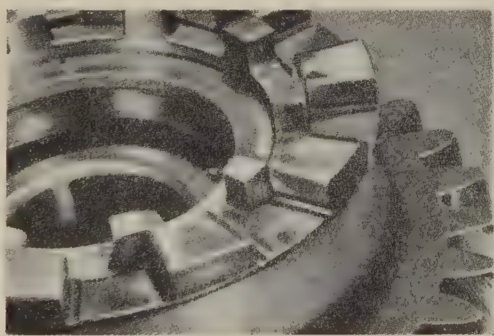

Fig. 11. — Single piece type locking dog-clutch.

to the bottom of the groove of the splined shaft (fig. 12). This phenonemon could only be explained by considering the way the clutch-claws work when the reverse gear is operated at the relatively high speeds of the two halves of the claw-clutch to be engaged. Under the influence of

the forces applied to the clutch, the claw ring (fig. 12, to the right) has a tendency to move out of place on the shaft (fig. 12, on the left) towards the right in the direction of the gear change. At each movement of one of the bevelled faces of the claw on the surface of the corresponding claw, there is a slight axial displacement of the sleeve. At high speeds of relative rotation, the axial frequencies become so high that the film of oil is destroyed at the points clearly seen in the figure; under the effect of slight axial movements of very high frequency then originate, in a time of about a second, such high temperature peaks that spot-welds are made between the ring and the splined shaft. When the technical causes were recognised, this defect was remedied by modifying the profile of the bottom of the groove, the modification of the oil inlet and some machining tolerances, as well as by the introduction of locking dog-clutches.

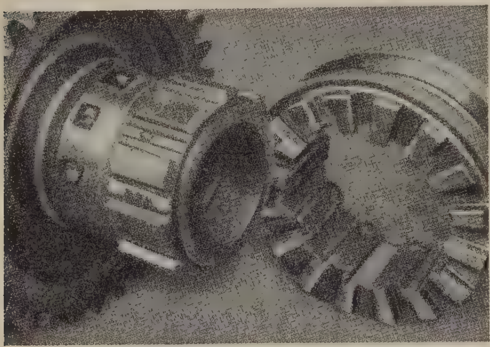

Fig. 12. — Shaft (on left) and ring with claws (on right) of the reverse gear clutch showing the formation of spot welds after the film of lubricating oil had been destroyed.

At the start of the practical use of these transmissions, their use on multiple-unit sets with a fairly high number of power installations caused some surprises. In the case of faulty synchronisation of the control mechanisms of all the transmissions, excessive heating of the torque converters occurred, especially if :

a) upon stopping a Diesel engine, the reverse gear did not return to neutral as a result of which the flux of the forces moved in the reverse direction, from the rail towards the turbine through the shaft from the transmission, so that the power absorbed was transformed into heat in the torque converter;

b) when running in multiple units, one installation was revolving in a lower gear ratio and was brought to a speed above the limit of this gear ratio by the other engines.

These defects were removed by :

a) modifying in a suitable fashion the clearance angle at the bottom of the

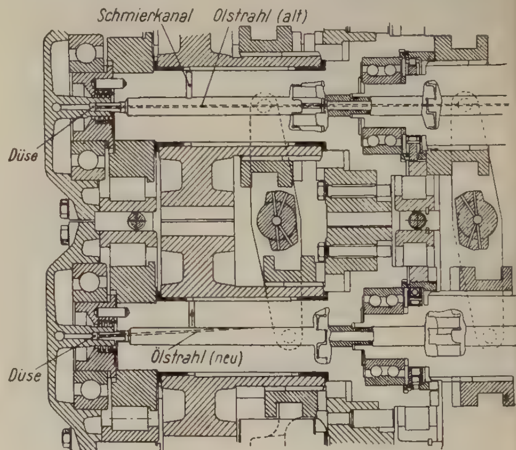

Fig. 13. — Lubrication of the hub support bush of the Maybach-Mekydro transmission. Formerly (shaft at top) : the jet of oil projected through the axially drilled hole went through the whole length of the hollow shaft without lubricating the bearings. Today (bottom shaft) the jet of oil is automatically projected against the hole in the shaft by the obliquely drilled hole and thus penetrates into the lubricating channel of the bushes.

N. B. — Schmierkanal = lubricating channel. — Ölstrahl = jet of oil. — (Alt) = (former). — (Neu) = (new). — Düse = nozzle.

side of the claws of the claw-clutch of the reverse gear, which facilitated the automatic disengagement;

b) by incorporating in the drive the « gear change valve » which changes to the next speed should the limits of a given speed be exceeded.

As in the case of the claws of the dog-

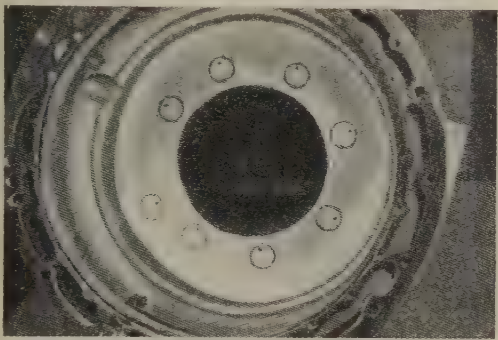

Fig. 14. — Inside wall of a torque converter gearbox with core stoppers.

clutch of the reverse gear, corrections were made to the sides of the claw-clutches for changing speed; these made it possible to increase the reliability of declutching operations.

These were all definitely characteristic « teething troubles », the result of small defects in the design. Such defects sometimes are only noticed under special operating conditions : in this case when working as a multiple unit with three engines and more. They could not be found during the usual trial runs with the dynamometer-car, and when running on the test bench, unless the possibility of trouble of this kind had previously been expected, and check the working of the clutch, the transmission had also been driven on the test bench from the secondary, at high power, or a trial made to exceed the normal speed of rotation.

One very instructive breakdown was due to a defect in the *distribution of the lubricating oil* in the so-called « hub support » bushes (Stielbüchsen) (fig. 13), which are used to carry the gears of the reverse gear in the transmission. These bushes, according to the original idea, were to be lubricated by a device for spraying the oil connected to the oil circulation under pressure. It was not easy to foresee that the nozzle, arranged on the longitudinal axis of the bushes, would spray oil over the whole length of the hollow shaft turning in the bushes, under the working pressure of 21.5 to 25.5 p.s.i., without the holes drilled in the shaft for the distribution of the oil getting any lubricant. A slight modification of the oil inlet, including a twin hole and the projection of the oil obliquely against the walls of the hollow axles made it easy to eliminate this defect which had caused some annoying breakdowns.

Figures 14 and 15 show the influence of *measures affecting technique and manufacture.* The silumin housings of the torque converters often developed leaks between the water space and the oil space,

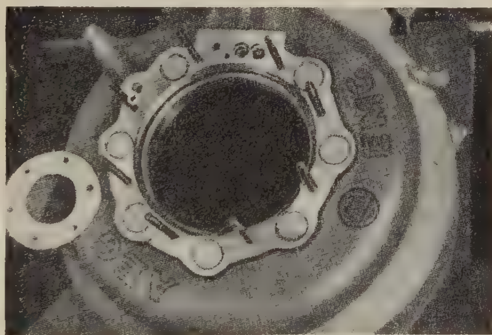

Fig. 15. — Converter gearbox with the core stoppers removed to the outside.

and it was found that the cause lay in locating the core plugs inside the housing (fig. 14). Moving them to the outer wall of the housing (fig. 15) put an end to these difficulties.

The first realisation of the Mekydro K 104 transmission was designed, like the

Voith transmission, for a power of 800 HP. The increase of the *power of the engine* involved in the case of this type of transmission with constantly full torque converter an enlargment of the cooling water jacket owing to the increase in the amount of heat to be evacuated, as well as some improvements in the design of this water jacket.

In addition, studies and trials are in hand, as we have said above, to allow of the emptying of the torque converter under certain circumstances, and thus avoid, when the engine is running light, losses of power due to a full converter, which amount up to 60 HP.

The observations made in the case of the Voith transmission concerning the emergency controls for manual gear change at first speed also apply to the Mekydro transmission; this latter includes, in case the electric remote control should break down, an emergency switch enabling a change into second speed to be made manually and attain in this way a speed of 60 km/h. At the present time, these transmissions have an emergency control making it possible to operate the transmission manually at all four speeds (fig. 16).

THE TRANSMISSION FLUIDS.

Our report would not be complete if no mention were made of the important work carried out for the constant improvement of the oils used as power transmitting fluids. The conditions that these oils have to meet are inherent in the nature of the problem. On the one hand, they are required to have sufficient lubricating power for the roller bearings and gears used, whilst on the other hand, it is necessary for them to have as low a viscosity as possible for the transmission to have a satisfactory efficiency, as well as, in the case of transmission working with emptying of the torque converter, to take into account the tendency of the oils to foam under these circumstances.

The progress made in the chemistry of lubricants in the last ten years is well known. These improvements have contributed to a large extent to the long working life of high duty Diesel engines at the present time, a life which would hardly have been considered possible some years ago. They have had

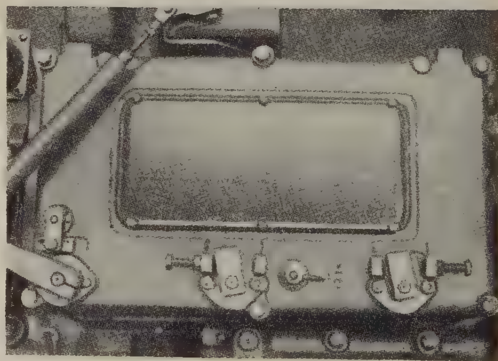

Fig. 16. — Emergency drive for Maybach transmission : *above*, new type; *below*, old type.

equally favourable repercussions on the development of hydro-dynamic transmissions. Today, by using certain additives, perfectly adequate lubricating properties can be given even to very fluid oils. The conditions of quality have been determined by long years of experiments and related to the viscosity, the point of solidification, flash point, combustion temperature, specific heat, specific gravity, the tendency to foam, the lubricating power, stability

against ageing, the necessary chemical compatibility with the metals, and various qualities of synthetic rubber for joints at all temperatures between the point of solidification and about 180° C, stability at the temperatures in question, and the ash content. The observation of the prescribed values is a preliminary condition for satisfactory operating.

THE EVOLUTION OF DRIVING MECHANISMS FOR HYDRAULIC TRANSMISSIONS.

The hydraulic transmission is the heart of the drive. But it cannot be used by itself; its application depends on the contrary in a decisive fashion on the choice of the elements of the mechanism by means of which the torque and the power are applied at the entry to the transmission and transmitted from the shaft at the outlet of the latter to the driving axles. Formerly, on account of the good experience obtained with rod drive, the hydraulic transmissions were first of all followed by spur gears and jackshafts, and the axles were driven by means of rods from these jackshafts. One of the most recent series of Diesel locomotives of the German Federal Railway, the V 60 shunting locomotive, has been fitted with this well-tried form of drive, because owing to the urgency of requirements for these locomotives, 270 had to be ordered immediately without any prototype, and without sufficient experience available concerning *cardan shaft drives* on shunting locomotives. However, this method of drive will also be tested in shunting services; experience to date with the line locomotive V 80, which is also used for shunting, shows that it gives good results in this case as well as in service on the lines.

It is no longer considered possible that the automobile designer would ignore using the *cardan shaft drive*. But in this case working conditions are more favourable, partly on account of the fact that the moments to be transmitted are lower, and partly because it drives wheels with pneumatic tyres through the intermediary of differentials. On the railways, it was used in the construction of railcars even before the war. In spite of numerous warnings, they had the courage to give up in the case of cardan shaft drives on railway vehicles, the use of differentials, thinking with reason that the stresses between the driving axles rigidly coupled by the cardan shafts would not be great enough to become dangerous for the mechanism. These previsions were founded upon the consideration that the torques transmittable are limited by the product of the coefficient of adhesion of the steel wheels on the rails by the load per axle.

When after 1948, Germany once more began to design new Diesel vehicles these experiences were remembered. To clarify the question completely, and ascertain the possibilities and limits of application of these mechanisms for the future, it was decided to equip with cardan shaft drive, in addition to the Diesel railcars with hydraulic transmission of 800 HP then 1 000 HP with two driving axles on a single bogie, the prototypes of the first medium power Diesel locomotive for mixed services (V 80). On this four axled locomotive, decisive progress was made : since *a single* Diesel engine drives by means of *a single* transmission two dividing gear boxes which in their turn *each drives two* motor axles *on the bogies.* At that time, the research department of the D. B. had a chance to study by means of extensometers in conjunction with oscillographs the stressing of these drives and their ramifications by the moments of torsion during working. The results expected from theoretical considerations as well as from the first trials with simpler cardan shaft drives were not merely confirmed; there was even greater satisfaction in finding that the stresses due to possible differences in the diameters of the circular tread are, even if there is no differential,

much less than the moments due to other operating circumstances, for example the moments of rotational acceleration due to slipping of the driving wheels. From the measurements and trials made during the summer of 1952, differences of up to 1.2 $^0/_{00}$ in the wheel diameters cause in the cardan shaft drive reactive torques, and consequently reactive powers much less than the values calculated from the axle load, the coefficient of adhesion and the running speeds; in addition, these reactive torques diminish as the running speed increases until they reach a practically constant value. These phenomena can be explained by the fact that the conical wheels of a single axle can be said never to follow an exactly equal circular track. As a result, and because of the elastic deformations of the contact surfaces (Hertz surfaces) between the wheel and the rail, there is a tendency for a certain pseudo-slip to occur at this point. In addition, the whole transmission system must be considered as being elastic.

During measurements made with the experimental VT 92 501 railcar of the Deutsche Bundesbahn, an exaggerated difference in the diameters of the circular tread was produced artificially. The diameter of the circular tread of one of the driving axles was reduced by 5 $^0/_{00}$ compared with those of the other wheels, which corresponds to a difference in radius of 4.75 mm between the wheels of one driving axle and the other rigidly coupled together by means of the cardan shaft drive. The maximum torque measured under these conditions, with an axle load of about 18 t, reach values of a little more than 500 mkg which fell to 300 mkg as the speed increased. Later measurements showed that as the tread of the turned wheels became smooth, the torques fell to about 200 mkg at high running speeds, and increased to about 350 mkg shortly before stopping. During difficult starts and when the wheels slip, torques of nearly 1 000 mkg were measured. The theoretical torque for which the cardan shafts were calculated amounted to more than 1 300 mkg. After making these measurements, there was no hesitation in giving up any idea of using a differential.

The importance of this observation lies not only in the fact that it makes it possible to save on the differential, and the weight and cost involved; even from the operating point of view there is a real advantage in the fact that the tendency to slip of the four driving axles coupled by cardan shafts, for example (V 80), is naturally lower than in the case of an individual axle drive with the same type of drive using a differential. In practice therefore with this arrangement favourable conditions are maintained when starting under difficult conditions with as high tractive efforts as possible at the driving wheels, just as in the case of the mechanism with wheels coupled by rods on steam locomotives.

The important measurements and trials which we have briefly reported were completed during the following year by very careful measurements of the working torques at the cardan shafts of the Diesel locomotives with four coupled axles (V 80) with a 1 000 HP engine. The object of and reason for these trials were the possibility of undesirable torsional vibration appearing. In addition to the results described above, they confirmed the results of the theoretical studies which had shown the importance of a judiciously arranged spring mounted anti-torque stop as well as the kinematically correct fitting of the cardan shafts according to predetermined angles in erection and out of line. The troublesome vibration noises which occur at certain locomotive speeds were then effectively overcome by constructional measures.

The constructional and metrological investigation then carried out on the mechanisms fitted beyond the hydraulic transmissions had as their object the improvement and perfecting of these drives with the possibility of future new locomotive studies in mind; they were carried out

with the greatest care with the essential collaboration of the Research Department, thermic technique section, of the Central Office of the Bundesbahn at Munich. The measurements were not only taken on the experimental V 80 and V 200 locomotives of the D. B. but also on types built by private firms, for example the Henschel DH 75 locomotive and the MaK V 2000 locomotive, by agreement with the builders, during running trials on the lines of the Bundesbahn.

tions during running under the effect of the reactive torques produced by the mechanism as a whole differ on the different cardan shafts according to their position and the stresses to which they were subjected. The irregularities amounted to as much as 12 % of the working torque, with peaks of as much as 50 % approximately.

However, as we have already reported, the peaks during slipping were very high. Figure 18 shows this variation of the tor-

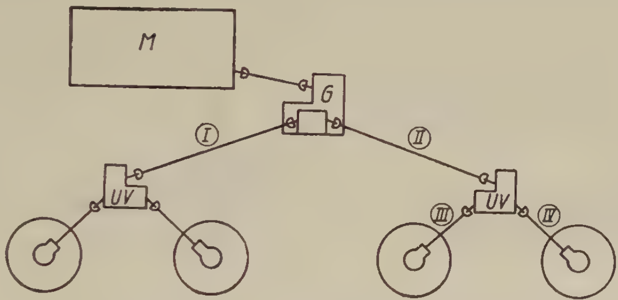

Fig. 17. — Diagram of the arrangement of the cardan shafts of the bogie Diesel locomotive with four coupled axles V 80 fitted with a single transmission having a power at input of 1 100 HP.

The results of these trials were most instructive in certain respects and are worth a detailed report, which unfortunately cannot be given in the present article. In view of the great importance of the constructive study of the drive mechanisms and the precise knowledge obtained of the stresses which occur, we are going to select and give a brief report of some of the results of the important measurements given by these trials.

At the end of 1955 new *measurements were made of the torque* on the secondary cardan shaft systems of a series V 80 Diesel locomotive (fig. 17). The measuring methods used were the same as previously.

The measurement of the *service torque* did not reveal anything special compared with the previous trials. Their fluctua-

que in a large cardan shaft connecting the hydraulic transmission to the switch and distribution gear for two axles of a bogie with two running speeds (20 and 10 km/h), the Diesel engine being in the top running notch 6. The maximum torque during slipping at V = 10 km/h for a short period rose as high as 1 500 mkg a value above the possible torque as a function of the axle load and coefficient of adhesion. The maximum torque on starting used as a basis for calculating the resistance of the shafts had been fixed prudently at 1 700 mkg and the breaking load on the shafts was about 4 000 mkg; consequently these peak torques did not constitute a danger for the transmission being studied here, but they are a critical factor for the calculations and constructional

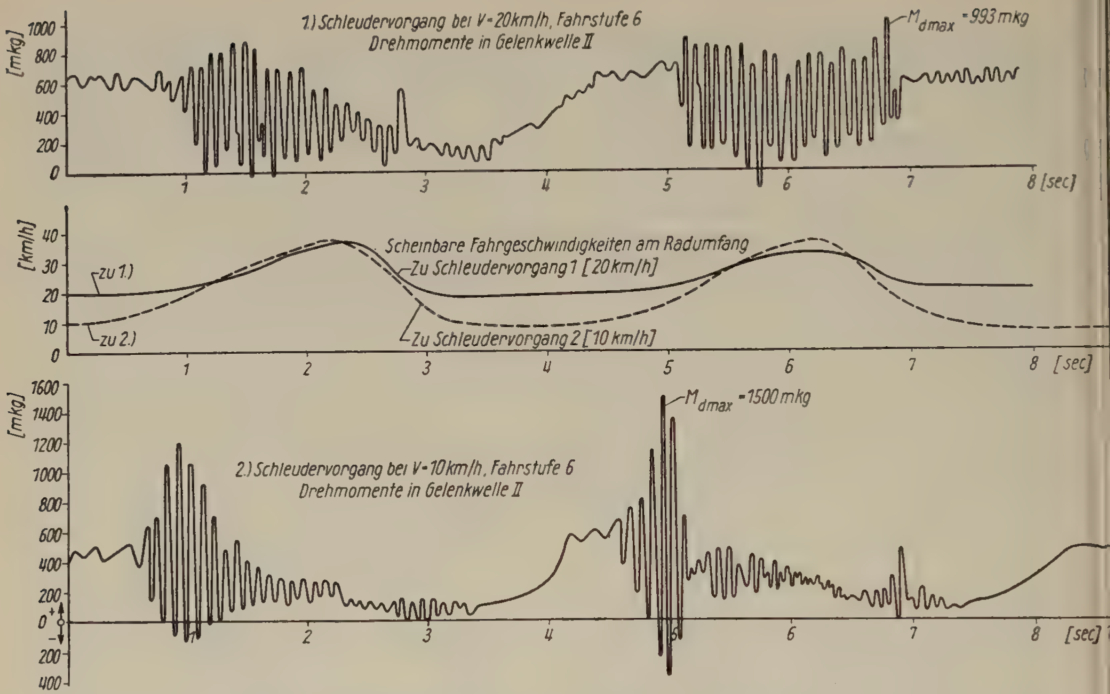

Fig. 18. — Variations in torque measured when slipping occurred on a large cardan shaft joining the hydraulic transmission to the switch and distribution gear for the two axles of a bogie on the V 80.

N. B. — Above : Slipping at V = 20 km/h, running notch 6; torques in the cardan shaft II. — Middle : Speeds shown at the periphery of the wheel. — When slipping : 1) (20 km/h). — When slipping : 2) (10 km/h). — Bottom : Slipping at V = 10 km/h, running notch 6; torques in cardan shaft II.

studies as a whole. The cause of this variation in the torque when slipping must be looked for on the one hand in the variations of the coefficient of adhesion and the slipping friction on the periphery of the wheel, but also and above all in the very variable values of the acceleration in the revolving masses.

The measurements made of the torque on the secondary cardan shafts of the Henschel DH 875 locomotive (fig. 19) gave practically the same results. The technique of measurements adopted in this case was a different one : the power of the engine was fully applied at the shunting regime of the locomotive, the rake being braked and the locomotive brake released (fig. 20, to the left). The curves show that in view of the very favourable friction conditions when stopped (apart from the small zig-zags which show a short period of slip of certain axles before the differences in torque were compensated) the locomotive exerted the whole of the maximum tractive effort on the train up to the moment the brakes of the rake were released when the train began to move slowly. At the first turn of the wheel, the locomotive began to slip badly and alternating torques of a high value amounting to as much as 2 000 mkg and over occurred, with a frequency of 6 to 8 Hz. The observations already made in connection with the measurements made on the

V 80 were thereby confirmed. Figure 21 gives the values of the speed of slipping and of acceleration corresponding to these torques.

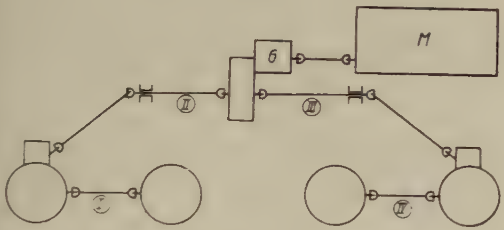

Fig. 19. — Diagram of the arrangement of the cardan shafts of the Henschel DH 875 four axled Diesel locomotive.

These tests were supplemented by similar trials, carried out in October 1956, with a 2 × 1 000 HP six-axled Diesel locomotive built by MaK at Kiel. Here it was desired in particular to find out the variation of the torque in the mechanism connecting the transmission to the three axles of a bogie, with the shaft arrangement shown in figure 22. The diagram of figure 23 which gives the results of measurements for the three shafts M I, M II and M III under different running conditions shows a distribution of the moments corresponding more or less to the arrangement. The precise analysis however gives values somewhat different from the theoretical value per axle (1/3 · of the input

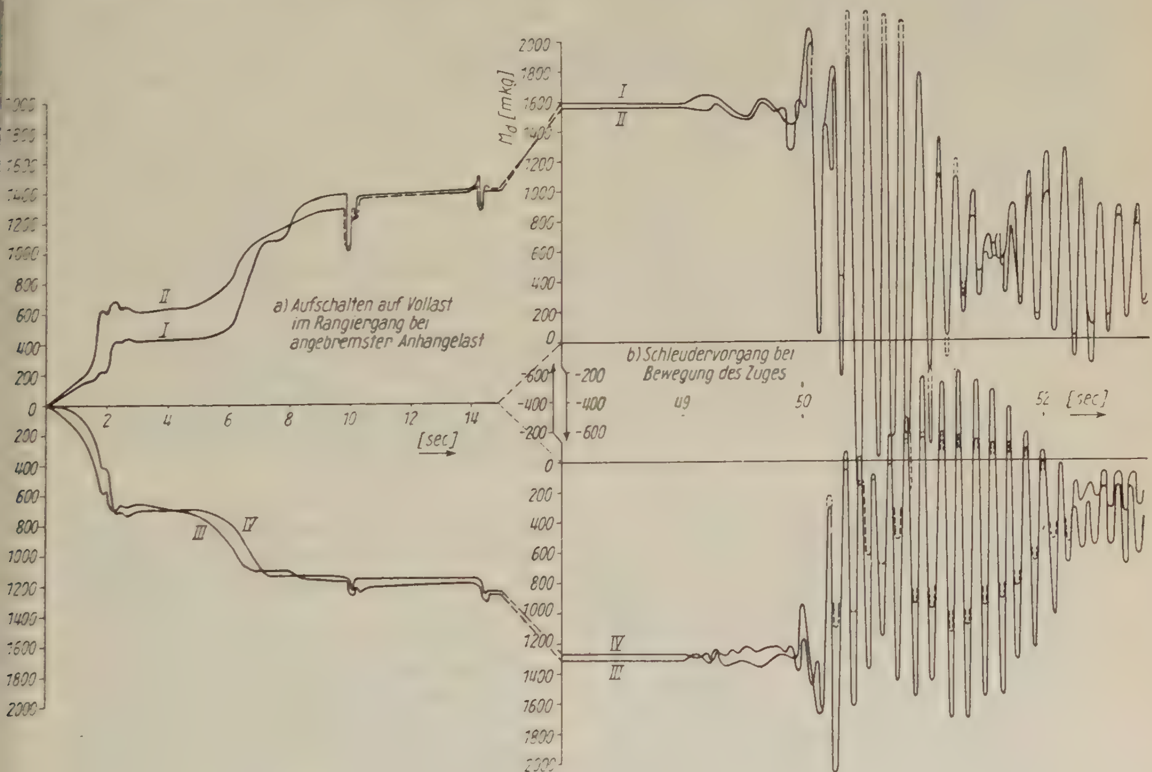

Fig. 20. — Measurements of the torque on the Henschel DH 875 locomotive. Variations in the torque measured on the four cardan shafts (fig. 19) when changing from one running notch to another and when slipping.

N. B. — *a)* Progression up to full load when shunting, the load hauled being braked;
b) Slipping when the train began to move.

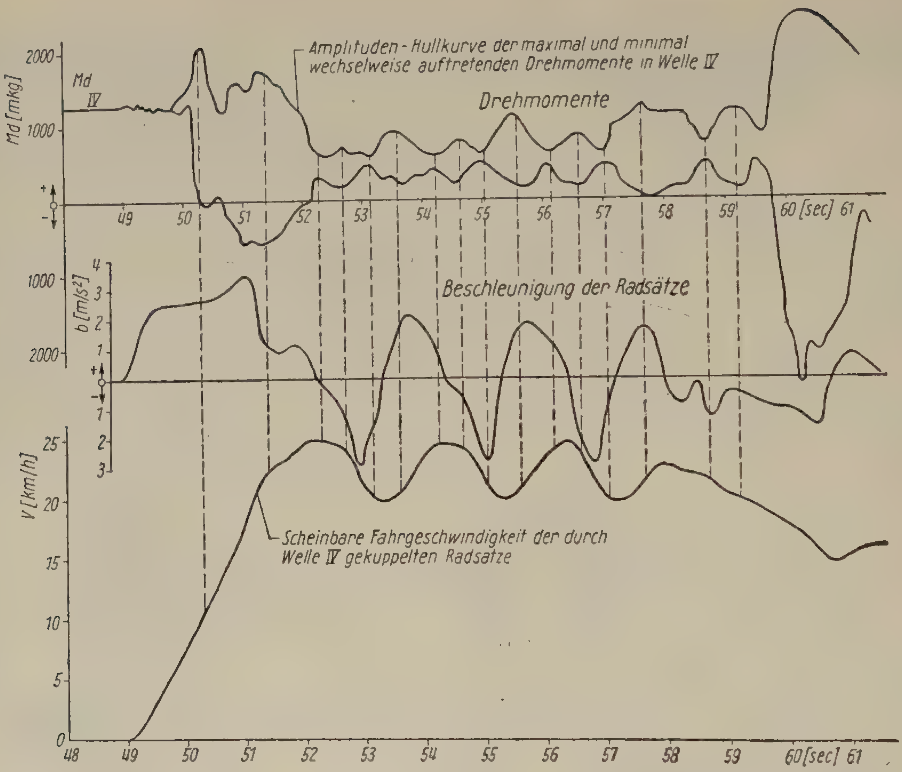

Fig. 21. — Torques, slipping speeds (peripherial speeds of the driving wheels) and accelerations at the tread during the trials shown in figure 20.

N. B. — Above : Curve enclosing the amplitudes of the maximum and minimum torques which occurred alternatively in shaft IV. Torques. — Middle : Acceleration of the axles. — Bottom : Apparent speed of the axles coupled by means of shaft IV.

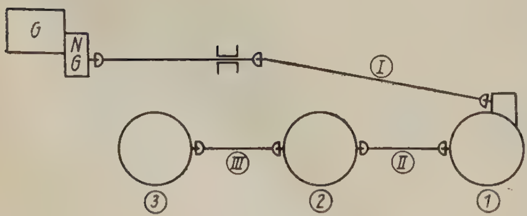

Fig. 22. — Diagram showing the arrangement of the shafts on one half of the six axled MaK 2 × 1 000 HP Diesel locomotive.

torque = 100 %) and in particular fluctuations between 95 and 145 % for shaft M I, between 50 and 133 % for shaft M II, and between 72 and 155 % for shaft M III. The cause of the differences lies essentially in the variable apparent torques.

As regards the maximum possible stresses taken as a basis for the calculations, these fluctuations remain insignificant. Likewise the drawback of the resulting small losses in power in the mechanism is small in comparison with the advantage of the total mechanical coupling of the drive arrange-

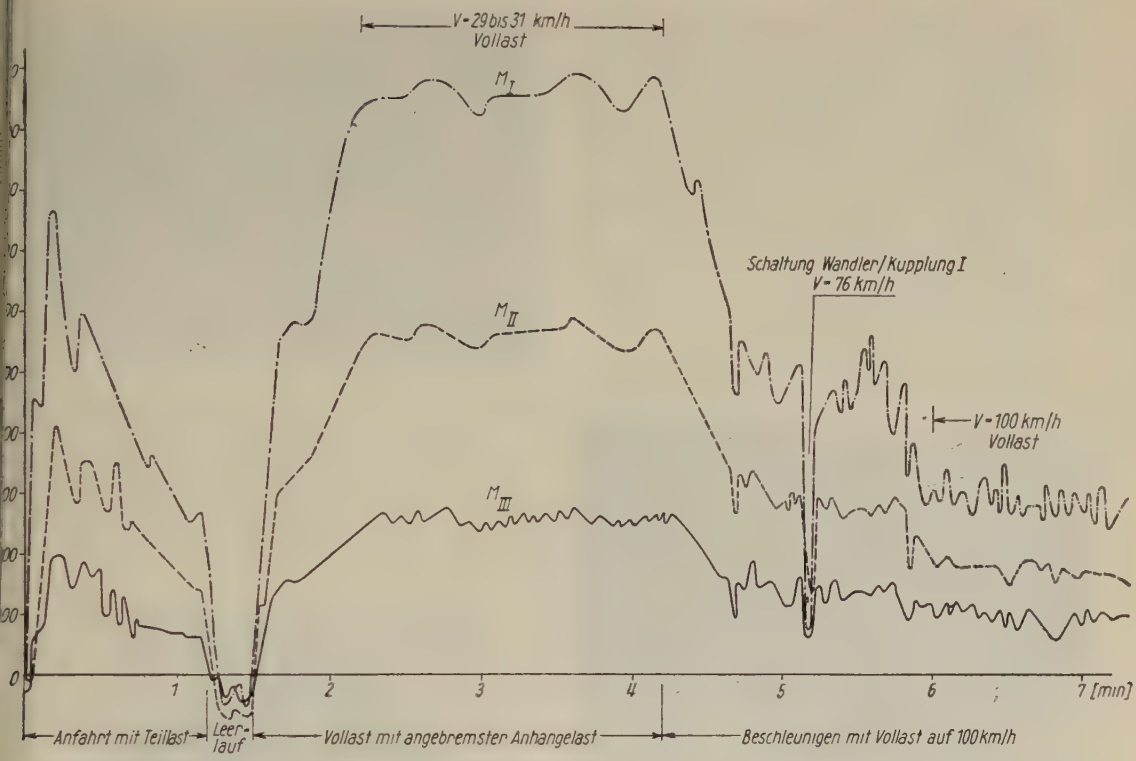

Fig. 23. — Variation in torque for the three measuring shafts of the MaK Diesel locomotive, according to the measurements made on starting at part load, no load, full load with the rake hauled braked, and in the case of acceleration up to 100 km/h.

N. B. — Vollast = full load. — Schaltung Wandler/Kupplung I = gearing converter/coupling I. — Anfahrt mit Teillast = starting under part load. — Leerlauf = running light. — Vollast mit angebremster Anhängelast = full load with hauled load braked. — Beschleunigen mit Vollast auf 100 km/h = acceleration under full load up to 100 km/h.

ments on the locomotives, which makes possible a better user of the adhesive weight than individual axle control and results in less tendency to slip.

EXPERIENCES IN SERVICE WITH CARDAN SHAFTS.

The cardan shaft intended to drive locomotives are infinitely heavier than those of the usual construction such as those used on automobiles. They had therefore to undergo considerable improvement before reaching their present degree of safety of working.

For example at the beginning the bearings of the pins of the *universal joints* showed signs of damage in the form of marks made by the needle roller bearings (fig. 24), owing to the excessive tightness of the bearing caps. This defect was eliminated by a slight reduction in the degree of tightness and a more careful fixing of the tolerances.

On the pinion faces, some seizing up was noticed due to insufficient lubrication (fig. 25). The desired improvement was only obtained by increasing the number of milled lubrication grooves with very careful chamfering of their edges.

The *needle roller bearings,* in which the pinions turn, also gave rise to difficulties. The first bearings which had no cage led to damage occurring due to the oblique position taken up by the needles. Cages in aluminium and even in sheet steel being insufficiently strong to stand up to the stresses, today massive steel cages are used with success (fig. 26 and 27) together with a spacing ring between the end of the cage and the pinion bearing.

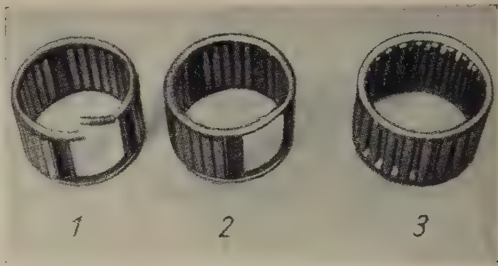

Fig. 26. — Needle bearing cages; 1 and 2 in sheet, 3 in solid steel.

The welding of the balance weights to the shafts, which have to be very accurately balanced (fig. 28), is currently practiced in automobile construction, but proved impracticable on account of the operating conditions to which railway vehicles have to stand up. The modification of the structure at the welding points favoured the formation of flaws which in their turn formed the starting point of stress cracks which led to the shaft breaking completely. Trials were also made of brazing the plates to the shaft but this method proved unsatisfactory : the assembly was uncertain and the plates came adrift. Defects in balance were then corrected on the flanges of the cardan shafts, a balance weight being welded on electrically; this method led to

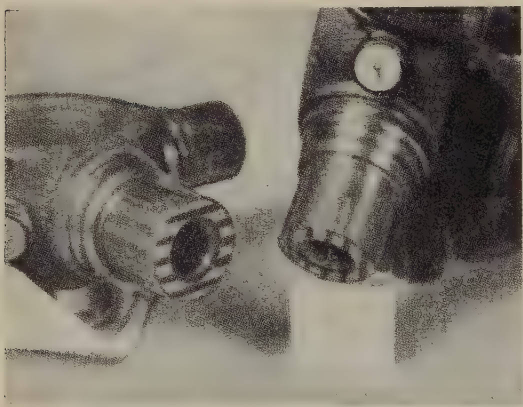

Fig. 24. — Indentations made by the needles on the pinion of the universal joints.

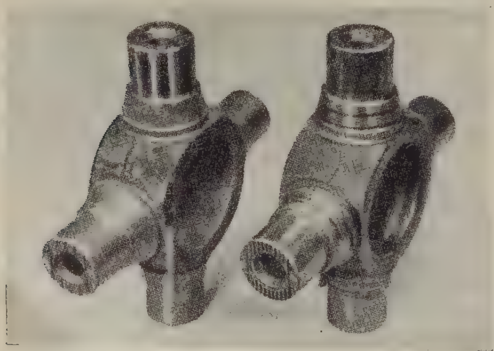

Fig. 25. — Increasing the lubrication grooves on the pinion faces from 5 to 11.

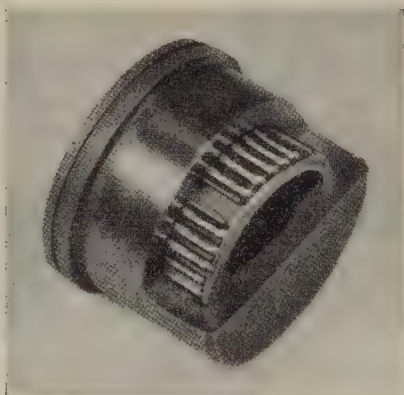

Fig. 27. — Needle bearing fitted, with solid steel cage and spacer ring.

Fig. 28. — Shaft with welded counterbalance weight.

the flanges breaking (fig. 29). The final remedy was only obtained by compensating defects in balance by means of holes drilled around the flanges of the cardan shafts (fig. 30). For some time, good results have been obtained from using the method which had proved satisfactory in electrical machinery, viz. the provision of adjustable dovetailed balance weights on the circumference of the shaft (fig. 31).

In general, the making of *welds* on these severely stressed parts is a serious fabrication problem. The hollow shafts used were originally slid over the flange and welded to it. This method of assembly had to be given up. The improved method then adopted which consisted in obtaining the connection by means of a V weld did not altogether give the results expected at the beginning. A very careful inspection with

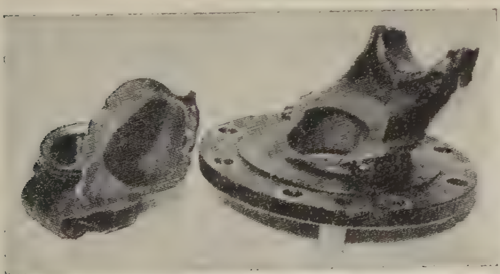

Fig. 29. — Flange fracture due to the electrically welded counterbalance masses.

amongst other things radiography of the welding points is necessary to make sure that there are no defects in the connection.

The solid shafts now used on short cardan shafts have given good results and it can be stated that at the present time the designing of the heaviest cardan shaft to drive railway motor units *no longer presents any difficulties.*

THE AXLE DRIVES.

It remains to deal with the last transmission component, the geared axle drive.

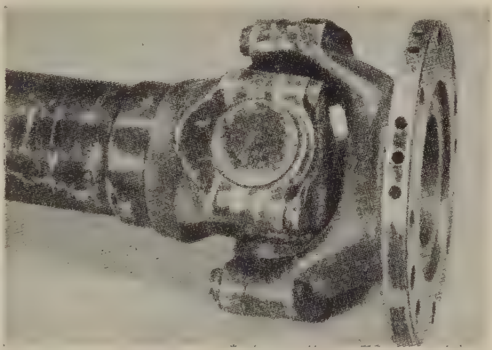

Fig. 30. — Compensation of defects in counterbalance by means of holes drilled in the periphery of the flange.

Fig. 31. — Adjustable counterbalance weight dovetailed on the shaft circumference.

Although this is not typical of the hydraulic system, it raises, on account of its dimensions and the high powers to be transmitted in the case of locomotives, serious problems as regards design and materials; its perfecting to make it completely suitable for the duties it has to fulfil was also marked by certain incidents and surprises.

On the new railcars and locomotives about 200 axle drives (Maybach C 32) have been used, and in later units (V 200 and TEE railcars) the same axle drive with a reinforced bevel wheel (Maybach C 33), about 300 of them. These mechanisms, which were perfected on the railcars, are built up very simply from a large bevel gear fixed on the body of the axle and a small conical pinion turning in the axle drive housing.

Difficulties arose at the beginning in connection with the *assembly of the conical pinions* as well as their lubrication. Improved lubrication by oil under pressure, the fitting of lubricating oil thrower discs between the two roller bearings with tapered rollers in order to improve the cooling obtained by the circulation of the oil, the correct arrangement of the oil spraying nozzles especially on the locomotive axle drives, without overlooking the use of assembling with oil under pressure in order to facilitate dismantling the bearings with conical rollers from the pinion shaft, gave the necessary improvements, after the play in the bearings which was very small to start with, had been increased to 0.1 mm. In addition to these measures, other grades of lubricating oils (hypoid oils) were used which made it possible to stand very high specific pressures between the teeth of the large gear and of the conical pinion.

The very high starting torques which sometimes occur in locomotive service, which give rise to a deflection of the bevel wheel, and a modification of the gearing characteristics in the axle drive could be withstood provided this ring was strengthened in its central part (disc with

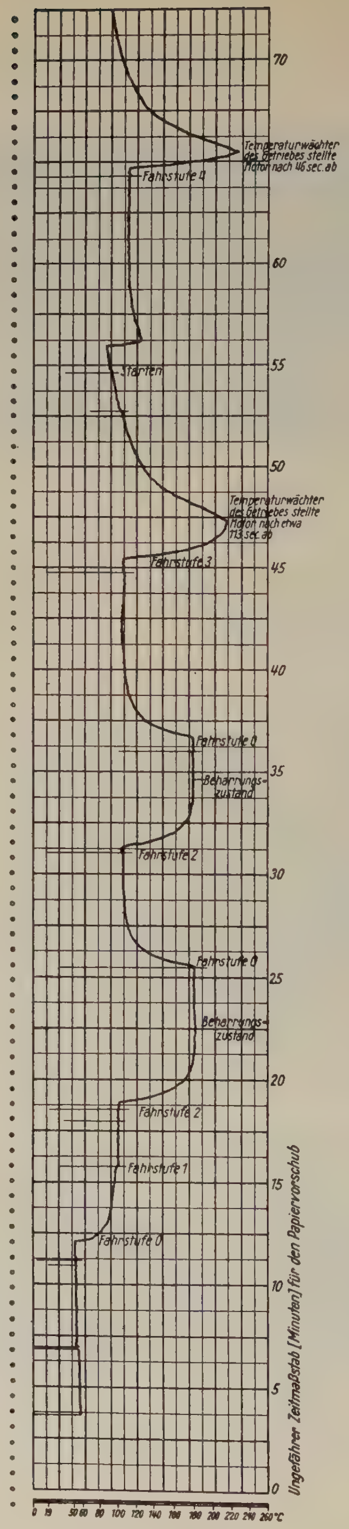

Fig. 32. — Temperature variations in the Mekydro transmission whilst measuring the tractive effort at standstill on the V 200 001 Diesel locomotive of the D.B. (15th March 1954).

N. B. — Fahrstufe = running notch. — Beharrungszustand = state of equilibrium. — Starten = starting. — Temperaturwächter des Getriebes = the thermostat of the transmission has cut out the engine at the end of 46 sec. — Ungefährer Zeitmasstab... = scale of approximate times of transport of the tape (in min).

very great deflection rigidity). Since then, it can be stated that the standard type of axle drive now used, no longer presents any problems.

THE OIL COOLING INSTALLATIONS.

The thermic calculation and dimensioning of the transmissions with their oil cooling installations is also of the greatest importance as is the supervisory equipment (thermostat with release relay) which automatically controls the variable operating conditions. One of the well-known great advantages of the hydraulic system is that, provided the hydraulic circuits and cooling installations are properly studied and suitably dimensioned, it is possible to transmit practically any power for practically any period, even when the locomotive is stationary (conditions operating on starting, when changing from a state of immobility to a state of movement). In order to determine the limits of the starting power from a standstill, which are required of a transmission, as well as its quickness of reaction to overcoming the admissible stresses, measurements were made on various types of large Diesel locomotives, both when moving and at standstill. During these trials, the transmissions were also subjected to severe tests under the most adverse conditions, such as those which may occur, for example, on engines with constantly full torque converters and a relatively small volume of liquid. In the spring of 1954, trials of this kind were carried out for example on the first V 200 locomotive of the D. B. Figure 32 shows the variation in the temperature of the oil of a converter when the power of the Diesel engine was applied to the fully braked locomotive. The successive trials — from bottom to top of the figure — show that after changing from notch 1, then notch 2, etc., each time a state of equilibrium of the temperature occurs; in addition the action of the thermostat of the control installation will be noticed, which cuts out the installation endangered when the temperature limit is reached if, through a mistaken movement, for example trying to start with the locomotive fully braked (exceeding the adhesion limit used as a protection against slipping), too high a running notch is selected. The diagram of the corresponding tractive efforts shows values of as much as 26.5 t [2] during these tests.

Similar trials were carried out during the summer of 1955 on the first prototype series V 60 locomotives of the D. B. An accurate knowledge of the admissible limit of the thermic stresses in the transmissions is of essential importance in the case of a Diesel shunting engine which, apart from starting up under difficult conditions has to work under conditions very similar to the trials reported above. Figure 33 shows the variation in the transmission oil temperature whilst such measurements were being made with a series type locomotive fully braked. The V 60 starting from standstill and braked to begin with can therefore, without endangering the mechanism, exert tractive efforts above the limits fixed by the normal adhesive weight and reaching almost the extreme limit of adhesion, depending in each case upon the state of the rails.

The curves also show that even when the locomotive is at a standstill, the Diesel engine can transmit permanently very high powers to the transmission without any fear of excessive thermal or even mechanical stresses. The indicated engine powers when the locomotive is at a standstill produce higher tractive efforts on starting than the limits set by the adhesive weight.

The studies and trials, which we have reported, were intended to ascertain the

(2) In this case the maximum effort possible has not yet been reached, owing to the fact that by a different regulation, one of the installations was switched out of gear, whilst the second, which had not yet reached its limit value, continued to turn.

mechanical and thermal limits of the whole of the system of transmission of power which must be taken into account in designing vehicles. The brief indications given show the care with which the work of drawing up the programme of the German Federal Railway and the work of designing carried out by industrial firms has been co-ordinated.

less serious, but which were all carefully and perseveringly studied because of their repercussions, occurred when the new designs of transmissions were first put into service. These have all been completely eliminated. At the same time, constructional improvements have been made in order to increase the mileage for certain important parts of the transmissions, and

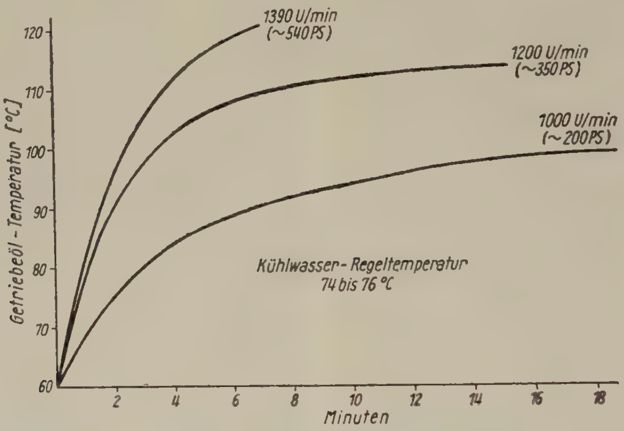

Fig. 33. — Variations in the oil temperatures of the transmission on a V 60 series locomotives with brakes full on.

N. B. — Getriebeöl-Temperatur = temperature of the transmission oil. — U/min = r.p.m. — Kühlwasser-Regeltemperatur... = normal temperature of cooling water 74 to 76° C.

THE GENERAL EXPERIENCES OF THE GERMAN FEDERAL RAILWAY WITH 1 000 HP TRANSMISSIONS.

In the above paragraphs, we have endeavoured by means of a few examples of the initial difficulties which are no doubt inevitable when any new designs are embarked upon, to show on the one hand that the slightest errors in design can have repercussions upon the working, for example service incidents on the motor unit, and on the other hand that the causes of such incidents can be completely eliminated by means of modifications, often extremely simple ones. Naturally, the cases mentioned above were not the only ones. A number of other incidents, most of them consequently of the transmissions themselves, between two overhauls in the shops. A description of all these very instructive stages in the perfecting of these transmissions would be too lengtly; we must however give a résumé of the measures which have favoured their evolution and improvement and thus made it possible to attain the *present high degree of quality of operation* of these powerful types of transmissions.

All incidents or defects reported were immediately studied very thoroughly by the Central Office of the Bundesbahn, at Munich, together with the makers, in order to determine whether the damage was due to :

a) outside causes (for example foreign bodies on the track);

b) operational mistakes, or

c) genuine technical defects.

The latter had to be avoided in the future by means of constructive measures or improved shop technique. Those parts of the transmission which showed any signs of damage were gone over very carefully. A distinction was made, for example, between the casing, the torque converter, the control and the clutch components such as the claws and sliding parts, the reverse gear controls, the roller bearings and toothed wheels and the rest of the equipment. Whilst under observation, which lasted for months and years, various weak points were noticed, amongst others — especially at the beginning — the reverse gear and some roller bearings, whilst the torque converters the controls and clutch components were rarely the cause of any service incidents.

The table illustrates the evolution of the *mileage run* by the two types of transmission considered. It shows, after the first experimental use in 1952, the increases in the mileages run since 1953 separately for each type, without showing, it is true, whether these mileages were run by railcars or locomotives.

This table shows that the Voith and Maybach transmissions since they were put into service have run 25 to 32 million kilometres respectively on units of the Deutsche Bundesbahn; the *mileages run without incidents,* which at the beginning were only 40 000 and 60 000 km had already been increased by 1955 to about 100 000 to 200 000 km, and during the third quarter of 1956, they reached a value very close to half a million kilometres for the transmissions of the most recent tyype. In these statistics, have been considered as cases of « damage » or « incidents », every defect, even insignificant, which led to any disturbance in the train working or which could not be eliminated without removing and dismantling the transmission.

The experience of the last four years has shown how well founded were the considerations on which the D. B. had based their policy; the hopes put in the economy of hydraulic transmissions and their safe functioning have not been proved wrong; in fact, in many respects already they have even been surpassed. It is therefore to be expected that the fast Diesel engines used, which have many advantages from the point of view of price, weight and size, will also achieve the same operating qualities and safe functioning as the slower, heavier engines which have often been preferred to date in other countries; as a result they are already economically superior to them. The D. B. also continues to increase the mileage of hydraulic transmissions between two general overhauls, which in the end no longer depend on anything but the life of the roller bearings and gear; these parts have already reached a high degree of technical perfection and their useful life can be estimated very accurately. The method of working of the transmissions, which apart from the few parts already mentioned, do not include any other parts which slide against each other and might show appreciable wear, is very favourable in this respect, especially as all the parts are completely enclosed in an air-tight metal housing which prevents any dirt getting in. As moreover the oil tests, which have already proved their usefulness in the operation of Diesel vehicle engines can be used in a similar fashion to check the hydraulic transmissions, and serve as a reliable method of judging of the state of functioning and wear of the transmission, the checking of the latter can be further simplified in the future and only need take place after considerable mileages.

The Deutsche Bundesbahn will continue, naturally, to follow as in the past the development of electric transmission installations. However, from the results obtained in operation, they see in *the use of hydraulic transmissions very great advantages* which other methods of transmission and torque conversion do not have at present. In addition, and we shall return to this point, the possibilities of technical and constructional improvements to these

TABLE : **Transmission mileages.**

Type	Désignation	Year	1953	1954	1955	1956	1957	1er sem. 1958
Maybach	K 104	Number	19	19	19	19	19	19
		km since being put into service	2 965 000	4 555 000	6 363 000	8 443 000	10 870 000	11 958 000
		km/year	1 863 000	1 590 000	1 808 000	2 080 000	2 427 000	1 170 000
	K 104 US/SU	Number	3	20	20	27	73	88
		km since being put into service	106 000	2 153 000	4 889 000	7 345 000	14 352 000	21 707 000
		km/year	106 000	2 047 000	2 736 000	2 456 000	7 007 000	7 068 000
Voith	T 36	Number	28	28	28	27	27	26
		km since being put into service	2 092 000	5 132 000	9 221 000	12 848 000	15 935 000	17 625 000
		km/year	1 722 000	3 040 000	4 089 000	3 627 000	3 087 000	1 595 000
	LT 306*r*	Number	—	—	8	39	101	103
		km since being put into service	—	—	414 000	2 454 000	16 251 000	24 292 000
		km/year	—	—	414 000	2 040 000	13 797 000	8 261 000
Mileages for all the different types of transmission since being put into service.			5 163 000	11 840 000	20 887 000	31 090 000	57 408 000	75 582 000

The numbers of transmissions shown in the first line in each case represent the figures available at the beginning of the year and the transmissions put into service during the year. Consequently, it is impossible, to give any specific figures, such as « annual mileage per transmission ».

types of transmission are far from being exhausted; the German Federal Railway will therefore follow the operating results of their first series of heavy line and shunting locomotives of the Diesel-hydraulic type with the closest attention in the next few years and compare them with other existing possibilities.

TENDENCIES OF NEW PROJECTS AND THE EVOLUTION OF HYDRAULIC TRANSMISSION SYSTEMS.

The above very thorough report of the experience in service on the D. B. with the first large installations of hydraulic transmissions of an input power of 1 000 HP was intended to give the reader, who is not well acquainted with the subject, some idea of the studies and trials made with the powerful types of transmissions which have been going on for more than six years. By means of examples taken from practical experience we have shown how, thanks to the close collaboration between industry and the railway, which is the trial ground, the D. B. has gone step by step from experimental types to series types. The choice given here of isolated experiences should make this general view very close to reality; a description of the whole mass of knowledge acquired and their technical results is outside the scope of a review of this nature.

In the next few months or years practical experience of the types of transmission dealt with here will be rapidly extended. In about one to two years, it will be possible to make a considered judgment founded upon a more general basis concerning *their possible applications and qualities.* In fact, the average service mileage of the heavy locomotives alone has already exceeded the million figure.

By that time, the projects and work of perfecting the most modern systems of transmissions for similar or definitely higher powers of transmission will have made much progress. In this connection, it is only possible to give a brief indication about the transmissions to be put in service on the D. B. in the near future, either for trials and experience or already as standard designs.

In the field of *small powers,* a slighly more powerful transmission for locotractors is still needed. For this purpose, it would be possible to use amongst others the Voith type L 33 y three-speed transmission, which consists of a starting converter and two coupling speeds. The well known « Hydromedia » transmission, of the « Zahnradfabrik » of Friedrichshafen gear manufacturing works, which consists of a starting converter and two mechanical

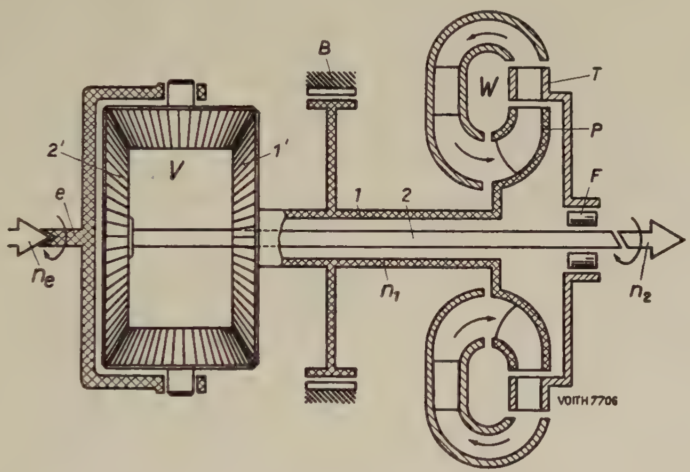

Fig. 34. — Diagram of the arrangement of the differential converter transmission. *V* distribution gear divider; *W* torque converter; *B* distributor brake; *P* pump impeller; *T* turbine runner; *L* guide vanes; *F* free wheel; *e* input shaft; *1* primary (hollow) shaft; *2* outpunt shaft. Figure taken from the article « Das Voith-Diwabus-Getriebe » (The Voith-Diwabus transmission), by Dr. Ing. Wilhelm GSCHING, which appeared in « Automobiltechnische Zeitschrift », 1953, No. 3; block by courtesy of Voith Company, Heidenheim.

speeds, and is an automatic type with a friction clutch, is worth attention. Trials might also be made, owing to the important principle involved, with a transmission working on the principle of the split drive (Voith-Diwabus type) [3]; this consists, as figure 34 shows, of a converter preceded by a planetary gear-train and

[3] « Automobiltechnische Zeitschrift », 55th Year, No. 3, March 1953.

braking devices together with a free wheel. The engine shaft, which on the left drives the planet carrier, controls by means of the left and right sun wheels both the output shaft leaving the transmission which is on the right and the hollow shaft of the hydraulic converter pump. During starting, the left sun wheel of the planetary gearing remains practically immobile because the drive wheels are either at a standstill or only rotating very slowly. Because of this, the right-hand sun wheel is driven by the engine shaft through the planet pinions at a higher speed and turns the pump shaft of the hydraulic converter; this latter transmits a considerable torque by means of the turbine blades and the free wheel through which the output shaft of the pump is connected to the output shaft of which we spoke above, should the speed of rotation of the pump shaft be exceeded. On starting, the drive wheels being at a standstill, and consequently the output shaft also at a standstill, the free wheel is coupled to this output shaft and the motor torque of the pump impeller is transmitted to it according to the characteristics of the converter. However, as the speed of rotation of the output shaft increases, the proportion of the power transmitted, not through the intermediary of the converter, but directly by the left hand sun wheel, increases until finally the whole of the torque of the engine is transmitted in a purely mechanical way as soon as there is no longer any positive difference in the speed of rotation of the pump impeller and the turbine-wheel of the converter and consequently no torque can be transmitted. It is clear that this principle may be of great importance in improving the efficiency whilst giving the characteristics such a form that automation can be largely used, even in the case of transmissions of high power.

For *medium powers* of about 350 HP on input to the transmission, four-speed hydro-mechanical transmissions made by the « Zahnradfabrik » at the Friedrichshafen gear works can be considered (type 4 HE 175) and by the Firm EMG/AEG (type SL 350/W 460). The use of these two types, which work in very different ways, may be considered in the case of railcars. They are susceptible of filling the gap between low and high powers. The former, built by the Friedrichshafen Gear Works, consists of a starting converter followed by three speeds with electro-magnetically operated friction clutches whereas the four speed hydro-mechanical transmission of the EMG has three converter stages (one converter) operated by friction gears and a fourth speed with direct drive like the small transmissions of the same type already described.

The series V 60 shunting Diesel locomotive, described above, is now being built as a special experimental type equipped with a Krupp (Lysholm-Smith principle) hydraulic transmission. This transmission includes devices which make possible the orientation of the blades of the pump-impeller when running light as a function of the control air pressure regulated by the driver by means of a wheel. If a greater power is needed, the speed of rotation of the engine is increased, whereas the blades of the pump-impeller remain open (speed regulation). If the power absorption capacity of the converter exceeds the available engine power, the absorption of power decreases automatically by the desired amount by the modification of the angle of the blades of the pump; this avoids having to reduce the speed of rotation of the engine. The efficiency parabola of the converter becomes flatter, owing to the possibility of regulating the blades of the pump and thus is spread over a wider range of working conditions. The emptying of the converter is not necessary, which assures great rapidity of reaction. This type of transmission which has already been fitted on the railways of other Administrations for powers of from 150 HP up to 2 × 1 000 HP, also deserves attention as it makes it possible to use a small number of circuits and stages and consequently obtain a light construction.

In the field of *relatively high powers*

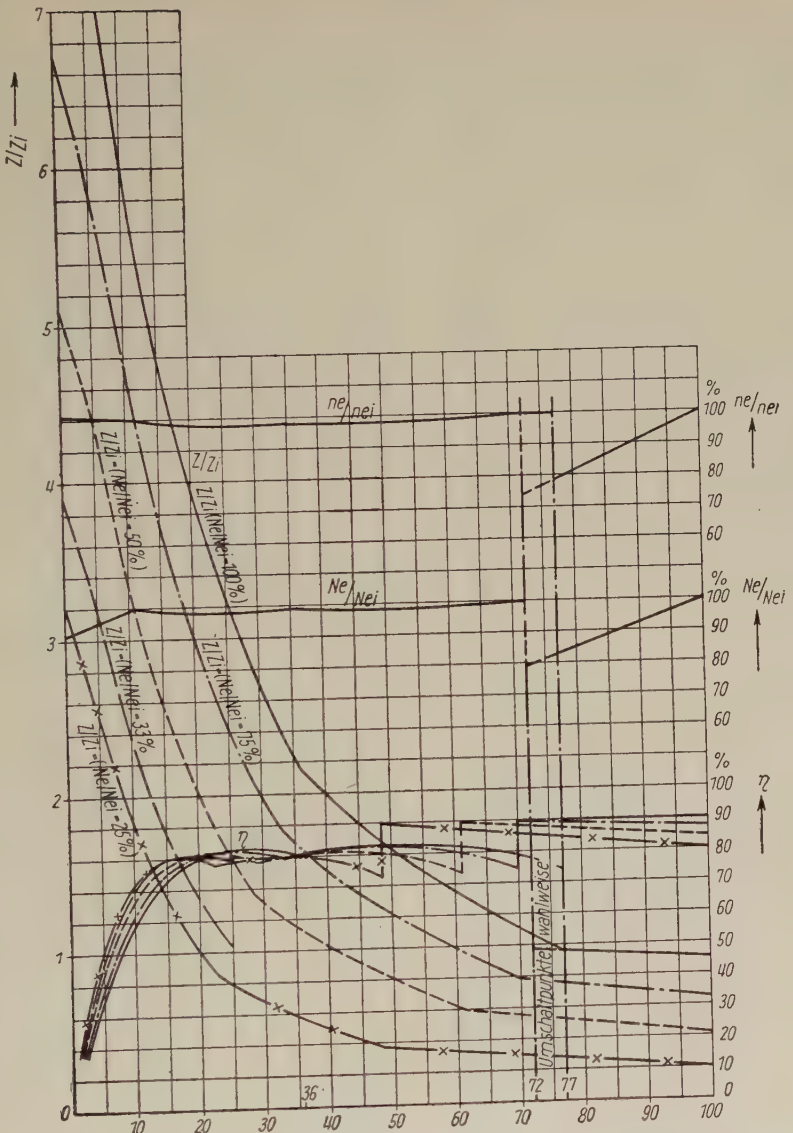

Fig. 35. — Part load curves for Voith L 217 *z* transmission with control by the primary. Established for Ne/Nei = 100, 75, 50, 33 and 25 %. Nei = 940 HP; q = 1.51; n_{ax} = 236 $\sqrt[3]{\text{Nei}}$; Ψ_x = 0.975.

— for example for a combined line and shunting Diesel-locomotive for secondary lines — a three-speed hydraulic transmission with an input power of 1 000 HP, type L 216 rs, an improved version of the Voith type, is to be tested and used. This includes mechanical demultiplications preceded at low and average speeds by two

torque converters, and at high speeds by a coupler, with reduction gears and reverse gear included. Figure 35 shows the calculated characteristics of a similar transmission (L 217 z); thanks to the action of the primary on the clutch operations, this behaves very well under part loads and makes it possible to obtain an overall efficiency of as much as 90 % in important operating ranges. With a skilful driver, a locomotive equipped with this transmission can run to a great extent in coupling steps and consequently in the most favourable overall efficiency ranges.

For very high powers, it is probable that robust locomotive transmissions, with an input power of 1 600 to 1 800 HP will be put on trial by the D. B. as well, making use of the experience acquired with the 1 000 HP transmissions already described. These new types also work according to the principles described above.

In conjunction with a reduction gear with two fundamental demultiplications, these large transmissions will make it possible to use the full installed power of the Diesel on the locomotives between very wide speed limits. At low rating — limited at the bottom of the scale by the limit of adhesion — it is possible to apply in a permanent fashion the whole of the power of the engine from very low speeds; in the higher ratings, it remains applicable up to high speeds, for example as much as 160 km/h. When running on the converters, the efficiencies will be comparable to those of the most recent electric transmissions; on the couplings, they may exceed the figures obtained with electric transmissions. The efficiency percentages measured at the drawbar will be still more favourable, on account of the reduced weight of the hydraulic system, and consequently of the locomotive, compared with the electric system.

In addition to these proposed projects and improvements, other modern principles will be followed up in studying new types of transmissions. When examining the characteristics and special features of transmissions with split-drive as the above mentioned « Voith-Diwabus », it can be appreciated what advantages in functioning and action can be counted upon, at the high powers also, if the improvements are taken in hand along these lines.

Mention must also be made of the *hydrostatic transmissions*. The low power types, made in the form of non-pivoting pumps with a axial piston have given very good results in the large cooling installations of long distance locomotives and railcars. In view of their advantages as regards reduced weight and small size, very reliable working, and ease of regulation, they have to a large extent replaced the old types of electric transmission with regulation of the power as a function of the temperature for this purpose. Trials of systems of this kind also for higher powers between the driving motor and the driving axle of the locomotive, consisting at the primary and at the secondary of oil pumps with axial pistons are still in the initial stages. Axial piston pumps of this kind have already been installed in fixed plants; however, their use as a transmission on locomotives still has certain difficulties at high powers, amongst others on account of the strict requirements they must meet regarding the technique of regulation and efficiencies under part load.

However, hydrostatic transmissions of this type have been fitted in recent years in Italy on small Diesel locomotives; the speed of rotation and consequently the torque on outlet are adjustable in a continuous fashion between satisfactory limits, apparently with satisfactory efficiencies at medium and full loads. The direction of rotation of the engines can be altered without shock by pivoting the swash-plate of the engine or of the oil pump to the other side of the zero point. The reverse gear, which is necessary with hydrodynamic transmissions, is therefore not needed in this case. In addition, it is possible to house the primary and secondary in a single housing, or to subdivide the secondary into several driving units and consequently to

make individual axle drives. The possibility of reversing the action of the transmission forces also makes it possible to brake hydraulically by means of these transmissions.

Unfortunately, these advantages go hand in hand with certain drawbacks of a constructional nature. One of these is the fact that the power transmitted is a linear function of the speed of rotation and the surface of the piston at equal oil pressure and pivoting angle, which raises problems of design in the case of high powers; in addition, the possible speeds of rotation are limited owing to the piston speeds and the peripherical speeds in the control level of the swash-plates. Because of this fact, the dimensions increase necessarily at high powers, as well as the weight per horse power. It may then become necessary to reduce at the high powers the speed of rotation of the fast Diesel motors before the input side of the transmission. In the same way, the torque conversion, which in general cannot exceed the ratio of 3 : 1 when the regulation is limited to the oil pump alone, often involves regulation by modification of the angle, of both the pump and the engine. This then leads to complications in the control and regulation.

It would be possible to device certain artifices by using oversize pumps in conjunction with the regulation at the same time of the oil pressure, or by installing mechanical reduction gears. Well known firms and specialists are now engaged on research work of this kind.

RESUME.

The article is limited to a report of the evolution of hydraulic transmissions, and more particularly the hydrodynamic systems retrospectively from the first post-war types to those types which have been sufficiently perfected to allow of their series production, from the low to the high powers. There was no intention of taking sides in the controversy between the partisans of the electric and hydraulic systems of transmissions, nor of exposing the types and working methods of these transmissions which have already been sufficiently described. It was merely intended to give an account of the results obtained in practice in railway operation. The considerable efforts that have been made and crowned with success in order to design entirely satisfactory and completely economic torque converters have been described in detail by means of the two appropriate types of high power transmission. The specialist will see how the complete confidence that is now placed in hydraulic transmissions by a large railway undertaking has been sufficiently justified for these transmissions to have the widest application on its railway system with the new Diesel engines.

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